***R*-parity-breaking SUSY solution to the R_b and ALEPH anomalies**

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(Received 8 August 1996)

We discuss an optimal *R*-parity-breaking SUSY solution to the R_b excess as well as the ALEPH four-jet anomaly. The latter arises from the pair production of a top squark via chargino decay at CERN LEP 1.5, 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. [S0556-2821(96)04423-2]

PACS number(s): 12.15.Lk, 14.65.Ha, 14.80.Ly

Two of the intriguing results from the CERN e^+e^- collider LEP which have attracted a good deal of theoretical interest are the R_b and the ALEPH four-jet anomalies. The first anomaly refers to the LEP 1 value of $R_b(\equiv \Gamma_Z^{b\bar{b}}/\Gamma_Z^{\text{had}})$ being $\sim 2\sigma$ larger than the standard model (SM) prediction [1,2]. The second refers to the anomalous four-jet events recently reported [3] by the ALEPH experiment at LEP 1.5, each of which seems to consist of dijet pairs with a common invariant mass ~ 55 GeV.

It is now widely recognized [4–6] 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 ($\tilde{\chi}_1$). The assumption of a *R*-parity-violating Yukawa interaction term would invalidate the canonical missing E_T ($\cancel{E}_T$) signature for superparticle production and thus the LEP 1.5 limit on chargino mass [7]:

$$m_{\tilde{\chi}_1} > 65 \text{ GeV.} \quad (1)$$

In this case, pair production of charginos at LEP 1.5 can offer a possible explanation for the ALEPH four-jet events as was recently suggested in Refs. [8–10]. In particular, Chankowski *et al.* [10] have discussed a variety of such *R*-parity-breaking supersymmetry (SUSY) solutions to the ALEPH anomaly, which can also account for the R_b excess. The purpose of this paper 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 squark 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 four-jet events as well as for the R_b anomaly.

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

$$W_R = \frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c, \quad (2)$$

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 nonzero but not both.

Let us briefly discuss the various *R*-parity-breaking SUSY scenarios that have been suggested as explanations of the four-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 ($e^+e^- \rightarrow \tilde{\nu}^* \tilde{\nu}$) followed by their diquark decays, through one of the λ' couplings, can then lead to a four-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 analyzed 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 disfavored by the precision measurements of electroweak observables [10]. More recently, there have been two suggestions based on pair production of charginos with mass ~ 55 GeV [8,9]. One of them [8] assumes the decay sequence

$$\tilde{\chi}_1 \rightarrow W^* \tilde{\chi}_1^0, \quad W^* \rightarrow \bar{q} q', \quad \tilde{\chi}_1^0 \xrightarrow{\lambda''} q_1 q_2 q_3, \quad (3)$$

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 disfavored on several counts. It shows much broader distributions in the difference of the dijet masses as well as their sum than those of 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 four jets if one applies the ALEPH jet algorithm. The other suggestion [9] assumes the chargino decay

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$$\tilde{\chi}_1^{\lambda'} \rightarrow \tau \bar{q} q' \quad (4)$$

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 addresses 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

$$M_3 = \frac{\alpha_s}{\alpha} \sin^2 \theta_W M_2 \approx 3.5 M_2 \quad \text{and} \quad M_1 = \frac{5}{3} \tan^2 \theta_W M_2 \approx 0.5 M_2. \quad (5)$$

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

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

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.,

$$\tilde{\chi}_{iL}^\pm = V_{i1} \tilde{W}_L^\pm + V_{i2} \tilde{H}_L^\pm, \quad \tilde{\chi}_{iR}^\pm = U_{i1} \tilde{W}_R^\pm + U_{i2} \tilde{H}_R^\pm, \quad (7)$$

$$\tilde{\chi}_i^0 = N_{i1} \tilde{B} + N_{i2} \tilde{W}_3 + N_{i3} \tilde{H}_1^0 + N_{i4} \tilde{H}_2^0.$$

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

$$\tilde{t}_1 \equiv \cos \theta_t \tilde{t}_R + \sin \theta_t \tilde{t}_L, \quad (8)$$

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

In the low $\tan \beta$ region of our interest, the SUSY contributions to $Z \rightarrow b \bar{b}$ 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

$$\Lambda_{1i}^L \approx - \frac{m_t V_{i2} \cos \theta_t}{\sqrt{2} m_W \sin \beta} \quad (9)$$

which favors 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

$$O_{ij}^L = - \frac{1}{2} (\cos 2 \theta_W \delta_{ij} + U_{i1} U_{j1})$$

and

$$O_{ij}^R = - \frac{1}{2} (\cos 2 \theta_W \delta_{ij} + V_{i1} V_{j1}) \quad (10)$$

favor 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 sizable b as well as Z couplings then implies that the largest SUSY contribution to R_b (δR_b^{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 favor negative μ over the positive μ region [5]. We shall, therefore, restrict ourselves to the former. We shall consider

$$\delta R_b^{\text{SUSY}} \sim 0.0020 - 0.0025 \quad (11)$$

to be a viable solution to the R_b anomaly. It would exactly account for the discrepancy between the current experimental value [2] of $R_b^{\text{expt}} = 0.2178 \pm 0.0011$ and the standard model value (for $m_t = 175$ GeV) of $R_b^{\text{SM}} = 0.2156$, as well as close the gap between the $\alpha_s(m_Z^2)$ estimates from LEP 1 and from deep inelastic scattering.

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

$$C_i^{L(R)} \approx \frac{m_t N_{i4}}{m_W \sin \beta} \cos \theta_t \tilde{\gamma} (\sin \theta_t \tilde{\gamma}), \quad (12)$$

with $i = 1, 2$. The Higgsino-dominated region corresponds to large $\tilde{H}_2^0$ components in $\tilde{\chi}_{1,2}^0$ and hence a large SUSY branching ratio (B_S) for top squark decay. This quantity is relatively small in the mixed region since only $\tilde{\chi}_2^0$ has a large $\tilde{H}_2^0$ component while $\tilde{\chi}_1^0 \approx \tilde{\gamma}$. Thus, the upper limit on B_S from the Collider Detector at Fermilab (CDF) Collaboration top decay data [18] favors the mixed region as well. We shall take a rather lenient value for this limit [5,6]:

$$B_S < 0.4. \quad (13)$$

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 δR_b^{SUSY} is obtained at small negative value of the top squark mixing angle ($\theta_t^- \approx -15^\circ$) and small top squark mass

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

which lies in between the LEP 1 limit ($m_{\tilde{t}_1} > 45$ GeV) [19] and the D0 excluded region ($m_{\tilde{t}_1} \neq 65 - 85$ GeV) [20]. LEP 1.5 imposes no additional bound on $m_{\tilde{t}_1}$ as the pair-production cross section for the right-handed top squark is small.

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

TABLE I. SUSY contributions to R_b (δR_b^{SUSY}) and to the top quark 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 $\theta_{\tilde{\tau}} = -15^\circ$.) For each set, the top row corresponds to the allowed MSSM parameter space in the R -conserving scenario.

	(M_2, μ)	$\tan\beta$	$\Gamma(Z \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0)$	$m_{\tilde{\chi}_1}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\tau}_1}$	δR_b^{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

A: (150, -40) GeV, B: (60, -60) GeV,

and C: (40, -70) GeV, (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 δR_b^{SUSY} in the respective regions. For the Higgsino-dominated point (A), $m_{\tilde{\chi}_1}$ is close to its LEP 1.5 limit (1). Still, δR_b^{SUSY} is smaller than the required value (11), while the contribution to top quark branching ratio (BR) exceeds the limit (13). On the other hand, the mixed region points (B, C) are seen to give viable values of δR_b^{SUSY} , while satisfying the B_S limit. Note that, in this region, the chargino mass is safely above the LEP 1.5 limit (1); the most important constraint is rather set by the requirement that

$$m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0} \gtrsim m_Z \quad (16)$$

which follows from the stringent LEP 1 bound

$$B(Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0) < 5 \times 10^{-5} \quad (17)$$

deduced from the negative search for acoplanar jets using the $\not{E}_T$ signature of $\tilde{\chi}_1^0$ [19]. The best values for δR_b^{SUSY} and B_S are obtained for point (C). However, it corresponds to a gluino mass of 160 GeV, barely above the Fermilab Tevatron lower limit [21].

We now turn to effects of R -parity breaking via the λ'' couplings. As the LSP ($\tilde{\chi}_1^0$) now undergoes hadronic decay, the $\not{E}_T$ signature is no longer applicable. Thus, the LEP 1.5 bound (1) is inoperative. Moreover, the LEP 1 bound (17) on Z decay into neutralinos is now replaced by

$$\sum \Gamma(Z \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0) < 3 \text{ MeV} \quad (18)$$

corresponding to the 1σ error in Γ_Z^{had} . This is weaker than Eq. (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 $m_{\tilde{\chi}_1} < 65$ GeV, while satisfying Eq. (18) so that chargino pair production at LEP 1.5 can be a source for the anomalous four-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 δR_b^{SUSY} simultaneously. Table I shows that it is possible to go down to $m_{\tilde{\chi}_1} = 58$ GeV within the constraint (18) in the Higgsino-dominated region. The top squark mass can then be reduced to 50 GeV so as to allow the two-body decay mode

$$\tilde{\chi}_1 \rightarrow \tilde{\tau}_1 b, \quad (19)$$

which shall be assumed later on. Reducing the chargino and the top quark masses has the effect of increasing δR_b^{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 $m_{\tilde{\chi}_1}$ below ~ 65 GeV by either of the above methods, while still satisfying Eq. (18). However, for the mixed region point C, which offers the best value for δR_b^{SUSY} , it is possible to achieve this by increasing $\tan\beta$. As Table I shows, one can go down to $m_{\tilde{\chi}_1} = 56$ GeV, within the above constraints, by increasing $\tan\beta$ to 2.6. Decreasing the top squark mass to 50 GeV ensures the two-body decay (19) with a soft b . Note that the large value for δR_b^{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 Fermilab Tevatron is no longer applicable.

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

$$m_{\tilde{\chi}_1} = 56 \text{ GeV} \text{ and } m_{\tilde{\tau}_1} = 50 \text{ GeV}, \quad (20)$$

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

$$\tilde{\tau}_1^* \xrightarrow{\lambda''} ds, \quad (21)$$

or through the R -conserving loop process

FIG. 1. Pair-production cross section for a 56 GeV chargino as a function of the sneutrino mass for the two different LEP 1.5 center-of-mass energies.

$$\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0, \quad (22)$$

followed by

$$\tilde{\chi}_1^{0\prime\prime} \rightarrow uds, cds. \quad (23)$$

We do not consider top squark decay modes with b quarks in the final state since these will lead to a large number of b

FIG. 2. Event distribution as a function of the number of jets after the initial partons have been clustered with Durham/JADE algorithms (27) and (28). Both decay modes of the top squark are shown.

FIG. 3. Event distribution (after clustering down to four 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.

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

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

On the other hand, one requires [23]

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

for the LSP decay to occur within 1 cm [24]. Note that the direct decay (21) dominates as long as λ''_{ids} is larger than the relatively modest limit of Eq. (24) *irrespective* of the other Yukawa couplings. Thus, the direct decay is at least as natural [25] as the alternative route via Eqs. (22) and (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 (LEP 1.5) 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 top squark (19) using a parton-level Monte Carlo program. Both the two-body (21) and the four-body (22) and (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]

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

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

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

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

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

$$y_{\text{JADE}} \equiv 2E_i E_j (1 - \cos\theta_{ij})/s > 0.022. \quad (28)$$

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

The five-jet events of Fig. 2 are then clustered down to four 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 four-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(b) shows the corresponding distributions in the sum of the dijet-invariant masses (the pairing decided by the minimum difference). For the direct top squark decay (21), this distribution is sharply peaked at 105–110 GeV, in agreement with Ref. [3]. The slight downward shift of the peak from $2m_{\tilde{\chi}_1}$ is due to the suppression of the soft jets ($E < \sigma_E$) as discussed above. On the other hand, the four-body decay of top squark via $\tilde{\chi}_1^0$, Eqs. (22) and (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) and 3(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 calculation. As these will, typically, result in a loss of efficiency, we leave this excess in normalization.

In summary, relatively light top squarks ($m_{\tilde{t}_1} \lesssim 60$ GeV) and charginos offer a viable MSSM solution to the R_b anomaly within the constraints of top squark 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 top squarks via chargino decay at LEP 1.5 can offer a viable solution to the ALEPH four-jet anomaly as well. The direct decay of top squark into a light quark pair is expected to be the dominant mode for $\lambda''_{ids} \gtrsim 5 \times 10^{-5}$. 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.

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