

# ALEPH Four-Jet Excess, $R_b$ and $R$ -Parity Violation\*

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## ABSTRACT

We review briefly the indications for some relatively light superpartners based on the  $R_b$  anomaly and discuss the dependence of the potential increase in  $R_b$  on the assumption about  $R$ -parity (non)conservation. We point out that the exotic 4-jet events reported by ALEPH may constitute a signal for supersymmetry with such a light spectrum and with explicitly broken  $R$ -parity. A parton level simulation shows that production of a pair of light charginos with their subsequent baryon-number violating decays (either through a stop or through a neutralino) could possibly give rise to this excess. The decay  $\chi_1^- \rightarrow \tilde{t}_1 b \rightarrow dsb$  with  $m_{\chi_1^-} \sim 60$  GeV and  $m_{\tilde{t}} \sim 52$  GeV leads to signatures very close to the experimental observations.

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Preliminary results from the LEP1.5 run (after the upgrade of energy to  $\sqrt{s} = 130 - 136$  GeV) include peculiar four-jet events reported by ALEPH [1]. They join the other, longstanding, “LEP puzzles”—the  $R_b$  and  $R_c$  anomalies. The presently measured values  $R_b = 0.2211 \pm 0.0016$  and  $R_c = 0.1598 \pm 0.0069$  [2] are  $3.4\sigma$  and  $1.7\sigma$  away from their Standard Model (SM) values (for  $m_t = 175$  GeV). The  $R_b$  anomaly is statistically more significant than the  $R_c$  one and it is reasonable to consider theoretical scenarios which predict a  $R_b$  larger than that in the SM, but with  $R_c$  the same. Even if  $R_c$  is fixed to its SM value  $R_c = 0.172$ , the value of  $R_b$  measured under this assumption,  $R_b = 0.2202 \pm 0.0016$ , is still  $\sim 3\sigma$  away. Considerable excitement has been caused by realization that the MSSM (*viz.* the minimal supersymmetric extension of the SM) presents such a scenario provided some of the new particles are light [3, 4, 6]. Specifically, it has been shown that significant increase in  $R_b$  is possible for small  $\tan\beta$  with light chargino and stop, and for large  $\tan\beta$  with light  $CP$ -odd Higgs boson and chargino and stop. These conclusions have been reached in the framework of  $R$ -parity conserving MSSM (henceforth called  $R_p$ MSSM).

In this note, we extend the discussion of  $R_b$  to the case of MSSM with  $R$ -parity broken explicitly ( $\not{R}_p$ MSSM) and show that a stronger increase in  $R_b$  can be expected and for a larger region of the parameter space (in particular, the relevant range for  $\tan\beta$  is wider). We then speculate on the physical significance of the ALEPH events and point out that they can be interpreted as having arisen from a chargino pair decaying *via*  $R$ -parity violating interactions. While both stop- and neutralino-mediated decays are possible, the former is distinctly the better alternative, especially if the stop is lighter than the chargino. Signatures closest to the experimental one are obtained for  $m_{\chi_1^+} \sim 60$  GeV and  $m_{\tilde{t}_R} \sim 55$  GeV. Such an interpretation also leads to a significant additional contribution to  $R_b$ .

We begin by briefly discussing the results for  $R_b$ . Within  $R$ -parity conserving MSSM<sup>1</sup>, the increase of  $R_b$  is not unconstrained. Not only must the perfect fit in the SM to the bulk of the precision data be maintained, several other experimental constraints must be satisfied (see [5, 6] for an extensive discussion) too. It has been shown that from this global point of view, in a realistic  $R_p$ MSSM,  $R_b$  can be as large as 0.2180(0.2185) for low and large  $\tan\beta$  respectively. Although still  $1.5(1.0)\sigma$  away from 0.2202 this is an interesting improvement over the SM prediction. In the first place, the overall  $\chi^2$  is much better. Moreover, the fitted value of  $\alpha_s(M_Z)$  is lower than in the SM fits to precision data ( $0.116 \pm 0.005$  and  $0.122 \pm 0.005$  respectively) thus affording better agreement with the values obtained from scaling violation in the deep inelastic scattering or lattice calculations<sup>2</sup>.

If  $R$ -parity is broken, several constraints coming from direct sparticle searches are relaxed. In particular, the D0 exclusion plots [8] in the  $(m_{\tilde{t}}, m_{\chi_1^0})$  plane are no longer valid [9] and limits on the  $(\mu, M_2)$  plane from chargino searches at LEP1.5 ( $m_{\chi^+} > 65$  GeV) and neutralino searches at LEP1 and LEP1.5 are relaxed. However, for small gaugino

<sup>1</sup>We assume for this case gaugino mass unification, *viz.*  $M_1 = (5/3) \tan^2 \theta_W M_2$ .

<sup>2</sup>The overall average of  $\alpha_s(M_Z)$  from the deep inelastic scattering,  $\tau$  decays and jet physics is  $0.117 \pm 0.003$  [7].

masses, the decays  $Z^0 \rightarrow \chi_i^0 \chi_j^0$  can significantly contribute to the total  $Z^0$  width, thus worsening the  $\chi^2$  fit for small chargino masses. This effect is almost independent of the assumptions regarding  $R$ -parity, but can be circumvented by relaxing the assumption of gaugino mass unification. The quality of the fit to the remaining observables depends on parameters irrelevant for  $R_b$ , and is not in conflict with an increase in the latter.

A sample of results for  $R_b$ , as a function of the chargino mass, obtained from a global fit in the MSSM to the precision electroweak data, without imposing constraints relaxed by  $R$ -parity violation and without assuming gaugino mass unification (*i.e.* neglecting the contribution of  $Z^0 \rightarrow \chi_i^0 \chi_j^0$  to the total  $Z^0$  width) are shown in Figs. 1 and 2 together with the corresponding values of the overall  $\chi^2$ . (The analogous fit in the SM gives  $\chi^2 \approx 18.4$ .) The particular dependence of  $R_b$  on the chargino mass arises due to specific properties of the chargino mass matrix which are strongly asymmetric with respect to the change of sign of the  $\mu$  parameter.

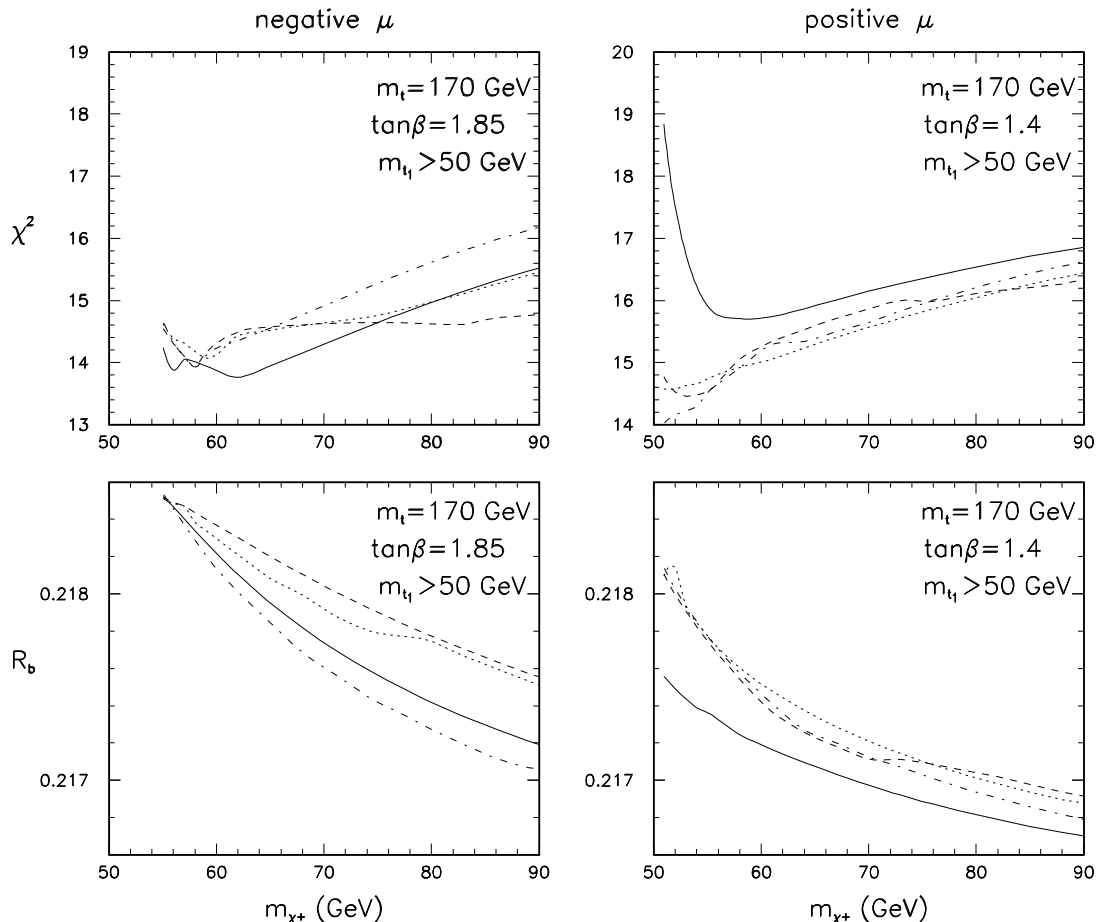


Figure 1:  $\chi^2$  (upper panels) as a function of  $m_{\chi^+}$  for  $r \equiv M_2/|\mu| = 0.5$  (solid lines), 1 (dashed), 1.5 (dotted) and 3 (dash-dotted) for  $m_t = 170$  GeV,  $\tan\beta = 1.85$  for  $\mu < 0$ ,  $\tan\beta = 1.4$  for  $\mu > 0$  and  $M_A = m_{\tilde{t}_2} = 1$  TeV. In lower panels the best values of  $R_b$  with the restriction  $\chi^2 < \chi_{min}^2 + 1$  (here  $\chi_{min}^2$  denotes the best  $\chi^2$  for fixed value of  $m_{\chi^+}$ ) are shown.

We see from Fig.1 that, for low  $\tan\beta$  and  $\mu > 0$ ,  $R_b$  (the overall  $\chi^2$ ) has a maximum (minimum) around  $R_b \approx 0.2180$  for light charginos ( $\sim 50$  GeV). For heavier chargino masses,  $R_b$  decreases rather rapidly (*e.g.* for  $m_{\chi^+} > 60$  GeV the best  $R_b$  is already smaller than 0.2176). For  $\mu < 0$ , a stronger enhancement of  $R_b$  is possible. As explained in ref. [5], this occurs for charginos that are strong gaugino–higgsino mixed states ( $r \equiv M_2/|\mu| \sim 0.5 - 1.5$ ), *i.e.* with both  $\bar{b}\tilde{t}_R\chi^-$  and  $Z^0\chi^+\chi^-$  couplings enhanced. This branch can support chargino masses in the 50–60 GeV range, but only for a larger  $\tan\beta$  ( $\gtrsim 1.8$ ) as compared to the other branch. Nevertheless, the values of  $R_b$  for the same chargino and stop masses are larger than for positive  $\mu$ . Although an increase in  $\tan\beta$  leads to a decrease of the top Yukawa coupling (and hence in the  $\bar{b}\tilde{t}_R\chi^-$  vertex), this is more than compensated by the increase in the  $Z^0\chi^+\chi^-$  vertex. Thus, for  $m_{\chi^+} \approx 55$  GeV and  $m_{\tilde{t}} \approx 50$  GeV, one obtains  $R_b \approx 0.2185$ . With  $\mathcal{R}_p$  one can take full advantage of the mechanism detailed in ref. [5], which now operates for very light charginos. It is interesting to observe that in the  $\mathcal{R}_p$ MSSM a sizable increase in  $R_b$  is possible for a relatively large  $\tan\beta$  range (1–2), with low  $\tan\beta$  values for  $\mu > 0$ , and larger values for  $\mu < 0$ .

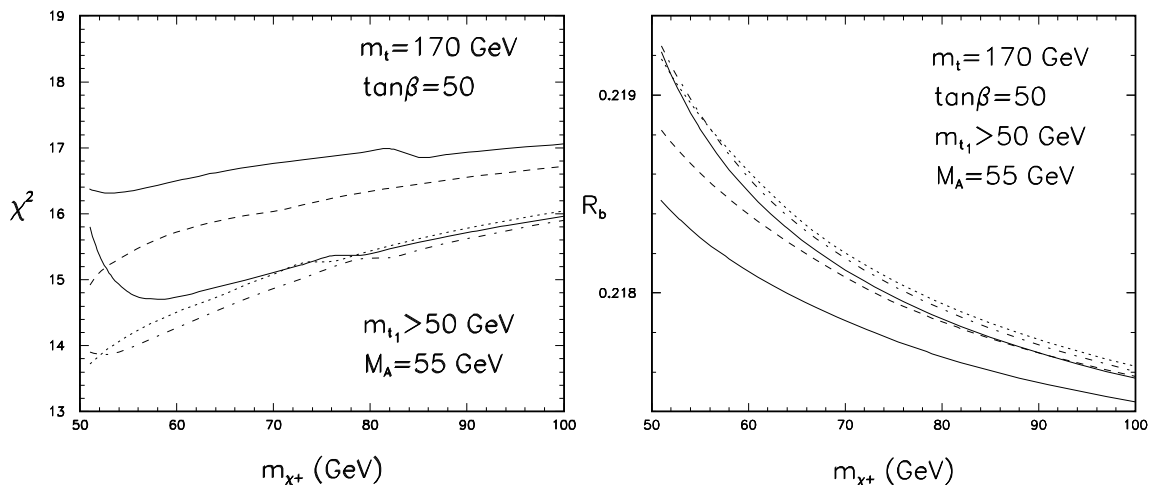


Figure 2:  $\chi^2$  (left panel) as a function of  $m_{\chi^+}$  ( $\mu > 0$ ) for  $r \equiv M_2/|\mu| = 1$  (upper solid lines), 1.5 (dashed), 3 (dotted), 5 (dash-dotted) and 10 (lower solid) for  $m_t = 170$  GeV,  $\tan\beta = 50$ .  $m_{\tilde{t}_2} = 1$  TeV,  $M_A = 55$  GeV,  $m_{\tilde{b}_R} = 130$  GeV. In the right panel the best values of  $R_b$  (with the restriction  $\chi^2 < \chi^2_{min} + 1$  as in Fig.1) are shown.

Significant enhancement of  $R_b$  is also possible for large  $\tan\beta$  values,  $\tan\beta \approx m_t/m_b$ . In this case, in addition to the stop–chargino contribution there can be even larger positive contribution from the  $h^0$ ,  $H^0$  and  $A^0$  exchanges in the loops, provided those particles are sufficiently light (in this range of  $\tan\beta$ ,  $M_h \approx M_A$ ) and non-negligible sbottom–neutralino loop contributions<sup>3</sup>

<sup>3</sup>The claim of ref. [4] that such a scenario is ruled out, has not yet been confirmed by an experimental analysis.

In Fig.2, we show the dependence of  $\chi^2$  and  $R_b$  on the chargino mass for a particular  $(m_t, \tan\beta)$  combination. As in Fig.1, we have imposed the condition  $m_{\tilde{t}_1} > 50$  GeV. The sbottom mass was fixed to 130 GeV. The main difference with the low  $\tan\beta$  case is the independence of the results on the sign of  $\mu$  (which can be traced back to the approximate symmetry of the chargino masses and mixings under  $\mu \rightarrow -\mu$ ) and monotonic decrease of  $R_b$  with increasing chargino mass. However, due to the combined effect of  $A^0$  and chargino-stop and neutralino-sbottom exchanges,  $R_b$  remains as large as 0.2178 even when all three masses  $M_{A^0}$ ,  $m_{\chi_1^+}$  and  $m_{\tilde{t}_1}$  are taken to be 65 GeV.

Thus, in  $\mathcal{R}_p$  MSSM,  $R_b$  can be much larger than is possible in  $R_p$  MSSM. The main change is that, with  $R$ -parity broken, the phenomenologically acceptable range of chargino masses is much wider than with  $R$ -parity conserved. In particular, for low  $\tan\beta$  both regions of positive and negative  $\mu$  are still of interest, and  $R_b \sim 0.2180(0.2185)$  is still possible for positive (negative)  $\mu$ .

In the context of  $\mathcal{R}_p$  MSSM one may speculate on the physical significance of the ALEPH four-jet events (apart from the light gluino window [10], lack of missing energy in these events excludes any interpretation within the  $R_p$  MSSM). One may even ask if both  $R_b$  and ALEPH events can have simultaneous explanation.

$R$ -parity is defined as  $R_p = (-1)^{3B+L+2S}$  [11] (with  $B, L, S$  referring to the baryon number, lepton number and the intrinsic spin respectively). It serves to eliminate certain  $F$ -terms that are otherwise allowed within the MSSM [12]. With  $L_i, E_i^c, Q_i, U_i^c$  and  $D_i^c$  denoting the superfields, these extra pieces in the superpotential can be parametrized as

$$W = \frac{1}{2}\lambda_{ijk}L_iL_jE_k^c + \lambda'_{ijk}L_iQ_jD_k^c + \frac{1}{2}\lambda''_{ijk}U_i^cD_j^cD_k^c, \quad (1)$$

where  $\lambda_{ijk} = -\lambda_{jik}$  and  $\lambda''_{ijk} = -\lambda''_{ikj}$ . While the first two terms in eq.(1) violate lepton number ( $L$ ), the last one violates baryon number ( $B$ ), and simultaneous presence of both can lead to rapid proton decay. Although  $R_p$  is a sufficient condition for suppressing proton decay, it is not a necessary one. In fact, the imposition of either baryon number or lepton number conservation is quite sufficient<sup>4</sup>. Investigation of the signature and possible consequences of a  $\mathcal{R}_p$  scenario is thus an worthwhile activity [14].

The  $L$ -violating couplings in eq.(1) are constrained mainly from data on lepton and meson decays [15]. Additional constraints also come from the lack of observation of a Majorana mass for the  $\nu_e$  [16] as well as LEP data on  $Z^0$  partial widths [17]. In the absence of  $L$ -violation, the strongest constraints on the  $\lambda''$  couplings come from low energy  $\Delta B = 2$  processes such as  $n - \bar{n}$  oscillations or double nucleon decays [18]. Further constraints can also be derived from the requirement that Yukawa couplings remain perturbative until the GUT scale [19] or from hadronic decay widths of the  $Z^0$  [24]. However, most such constraints turn out to be much weaker than the typical bounds on the  $L$ -violating couplings. Yet, most of the search strategies [20, 21] have focussed on the latter type. Part of the reason can be ascribed to the perception that  $B$ -violation at the

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<sup>4</sup>Even this might be too strong a requirement [13].

SUSY scale can wash out GUT scale baryogenesis [22]. However, Dreiner and Ross [23] have pointed out that such bounds are model dependent and can easily be evaded.

It is important to comment on the direct effect of  $\mathcal{R}_p$  couplings on the global fits and  $R_b$  in particular. As the analyses of refs.[17, 24] show, for moderate values of these couplings (of the order of the Yukawa couplings), these extra contributions to the electroweak precision variables are small. We have checked that the contribution to  $R_b$  remains at the level  $10^{-4}$  for a large range of parameters. Qualitatively, it follows from the fact that any loop contribution with  $\lambda''$ -type coupling is suppressed by the fourth power of  $\sin\theta_W$ .

Moreover, unless the relevant couplings are surprisingly large, implementation of  $\mathcal{R}_p$  into the MSSM has little impact on the cross sections for the production of superpartners. The decay signatures are drastically changed though. Since the lightest supersymmetric partner (LSP) is no longer stable, it will, normally, decay within the detector thus calling for a modification of most search strategies. One may then speculate that the recently observed 4-jet events in the ALEPH detector at LEP1.5 originate in the production of a supersymmetric particle which subsequently decays via  $\mathcal{R}_p$  couplings.

With an accumulated luminosity of  $\sim 5.7 \text{ pb}^{-1}$  at  $\sqrt{s} = 130 - 136 \text{ GeV}$ , and after the application of several selection criteria, ALEPH observes 16 events with 4 (or 5) jets where the SM expectation is only 8.6. Of these events, 5 are peaked around a combined mass of 105 GeV, with a spread of 6.3 GeV. Further, the events are consistent with no missing energy. As the SM expectation for the same interval is only 0.4 events, the probability that the excess can be explained by fluctuations is less than  $10^{-4}$ . Assuming the excess events to be a signal, the data is indicative [1] of a particle ( $X$ ) of mass  $m_X \sim 55 \text{ GeV}$  with a pair-production cross section of

$$\sigma(e^+e^- \rightarrow X\bar{X}; \sqrt{s} \sim 135 \text{ GeV}) = (3.7 \pm 1.7) \text{ pb}, \quad (2)$$

Of particular significance is the fact that *at best 1 event* is consistent with a  $b\bar{b}b\bar{b}$  final state, thus ruling out the possibility of the supersymmetric Higgs boson production,  $Z^0 \rightarrow A^0 h^0$ . This very fact renders difficult any explanation within the  $R_p$ MSSM. The only suggested counterexample [10] interprets these events to be pair-produced squarks decaying into a quark and a *light* gluino ( $m_{\tilde{g}} \sim 1 \text{ GeV}$ ). As the latter decays only after hadronization, the (missing) energy carried by the daughter photino is too small to be a good signature. While interesting, this scenario is not particularly helpful to the explanation of the “ $R_b$  anomaly”.

Within the regime of  $\mathcal{R}_p$  MSSM, the simplest explanation would then be one where  $X$  is one of the sfermions and is also the lightest supersymmetric particle <sup>5</sup>. It would then decay via the couplings of eq.(1) into two fermions. Since an explanation of the  $R_b$  anomaly prefers a relatively light  $\tilde{t}_R$ , it is tempting to identify it with  $X$ . The low production cross section ( $\sim 0.4 \text{ pb}$ ) rules out such an explanation though. In fact, only two kinds of sfermions,  $\tilde{\nu}_e$  and  $\tilde{d}_{iL}$  may have the requisite large production

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<sup>5</sup>Since the LSP is no longer stable in the presence of  $\mathcal{R}_p$ , one is not constrained, phenomenologically, to require it to be a neutralino.

cross section. The cross-section for  $\tilde{\nu}_e$  production may be enhanced in the presence of a relatively light (and gaugino-dominated) chargino [21]. With the sneutrino decaying through a  $\lambda'$ -type coupling, this could explain the ALEPH events. A detailed analysis has not yet been performed. Speculations [25] relating ALEPH events to the production of left handed squarks are strongly constrained by the LEP1 precision data. New sources of the custodial  $SU_V(2)$  breaking in the left handed squark sector are dangerous for the  $\rho$ -parameter and the related observables such as  $M_W$ ,  $\sin^2 \theta_{eff}^{lept}$  etc. . We have performed global fits to the electroweak data with a light ( $\sim 55$  GeV)  $\tilde{b}_L$  for  $m_{\tilde{t}_1} = 115$  and  $\tan \beta = 2.4$  (the case discussed in [25]). While we agree with the authors in the evaluation of  $\Delta\rho^{SUSY} (= 0.00285)$ , the fit to 11 electroweak observables not involving heavy flavours (*i.e.*  $R_b$ ,  $R_c$ ,  $A_{FB}^{0b}$  and  $A_{FB}^{0c}$ ) gives  $\chi^2 \sim 29$  which should be compared with  $\chi^2 \sim 7$  obtained for the case of a heavy  $\tilde{b}_L$ .

Since the production cross sections for a neutralino of mass 55 GeV is too low, we are left with a light chargino ( $m_{\chi^+} \sim 55$  GeV) as the most interesting candidate to explain ALEPH events. It survives both the total production cross section test (see Fig.3) and at the same time can explain the  $R_b$  anomaly. It is, therefore, interesting to study the effective chargino production cross section (with ALEPH cuts) and its decay signatures in the  $\mathcal{R}_p$ MSSM. In the rest of this analysis, we shall be conservative and confine ourselves to the  $\mu > 0$  branch. The results for  $\mu < 0$  are qualitatively very similar (though it is more advantageous for  $R_b$ ). We report here on a simulation at the parton level, followed by a brief comparison with ALEPH observations.

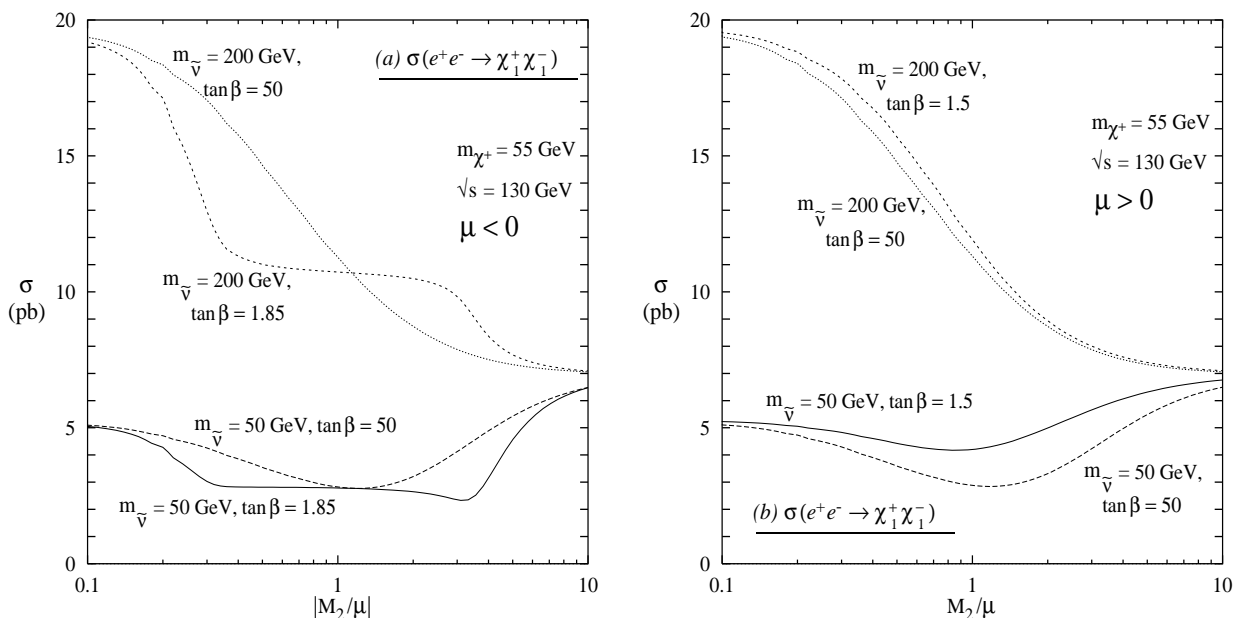


Figure 3: Typical chargino pair production cross sections, at LEP1.5. (a) for  $\mu < 0$  (b) for  $\mu > 0$ .

If the chargino were to decay through a  $L$ -violating coupling, one should see a relatively hard isolated lepton or have considerable missing momentum in the event. Since such events have not been reported, we shall here follow a different track, namely consider the  $\lambda''$ -type couplings<sup>6</sup>.

The chargino  $\chi^+$  may then decay via either of two channels (the asterisk symbolising possible offshellness)

$$\chi^+ \rightarrow \tilde{q}_1^* q_2 \rightarrow q_2 q_3 q_4 \quad (3)$$

or

$$\chi^+ \rightarrow \chi_1^{0*} W^* \rightarrow \chi_1^{0*} f_1 f_2 \quad (4)$$

$$\hookrightarrow q_3 q_4 q_5$$

with the neutralino ‘decaying’ via an  $\mathbb{R}_p$  mode. The chargino branching ratios depend on the assumptions and are *a priori* unknown. For example, if we have  $\tilde{q}_1 = \tilde{t}_R$  with  $m_{\chi^+} - m_b > m_{\tilde{t}_R} \gtrsim M_Z/2$ , the channel (3) would tend to dominate ( $\gtrsim 90\%$ ), irrespective of the neutralino mass. On the other hand, if the squark was more massive than  $\chi^+$  and the neutralino less, the branching ratios would, in a large part, be determined by the size of the relevant  $\mathbb{R}_p$  coupling. It should be noted that a coupling like  $\lambda''_{t ds}$  is rather weakly constrained [24, 19] and could still lead to a 50% branching fraction for the stop mediated decay (even if the stop is significantly off-shell). The situation changes yet again if both the squark and  $\chi_1^0$  are heavier than the  $\chi^+$ . Though such an eventuality does not occur in a scenario with gaugino mass unification, it is instructive to bear this possibility in mind. In view of the myriad possibilities, we shall discuss the two cases separately assuming the corresponding channel to be dominant.

As we are attempting only a parton level simulation (without incorporating hadronization effects), it is not possible for us to mimic the exact experimental cuts<sup>7</sup>, but we shall try to be as close to the experimental situation as possible. At the parton level we shall often encounter more than 4 quarks but not all these will lead to visible jets. The reasons are manifold. Some of the jets may be soft or too close to the beam axis and hence missed by the detector. To eliminate these, we impose cuts on the energy and rapidity of jets:

$$E(\text{jet}) > 0.1\sqrt{s}, \quad \eta(\text{jet}) < 3. \quad (5)$$

Any jet thus missed will contribute to the missing energy which is bound by

$$E_{\text{missing}} \lesssim 0.3\sqrt{s}. \quad (6)$$

To distinguish jets, ALEPH imposes a Durham  $y$ -cut of 0.008, *i.e.*, for any jet pair ( $ij$ ) to be distinguishable, they require

$$y_{\text{Dur}} \equiv 2 \min(E_i^2, E_j^2) (1 - \cos \theta_{ij}) > 0.008, \quad (7)$$

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<sup>6</sup>To the best of our knowledge, sneutrino pair production is the only possible scenario where a decay via the  $\lambda'$ -type couplings may have a role to play.

<sup>7</sup>Outstanding examples of such selection criteria are number of charged tracks per jet, masses of individual jets *etc.* .



where  $E_i$  is the energy of the jet  $i$  and  $\theta_{ij}$  is the angle between them. Any pair whose momenta do not satisfy the above condition will then be merged to form a single jet with momentum given by the sum of the constituent momenta, with the process to be repeated iteratively<sup>8</sup>. An identical procedure is adopted with regards to a JADE  $y$ -cut:

$$y_{\text{JADE}} \equiv 2E_i E_j (1 - \cos \theta_{ij}) > 0.022 . \quad (8)$$

To qualify, an event should have 4/5 distinguishable jets at this stage. In case of 5 jets, the pair with the smallest invariant mass are to be merged to form a single jet. We are then left with 4 jets and hence 6 ways to pair them. Each such pairing must satisfy

$$m_{ij} > 25 \text{ GeV} . \quad (9)$$

For the sample that has survived these cuts, jets are paired by selecting the particular combination with the *smallest* invariant mass difference which has then to satisfy the condition

$$\Delta m \equiv \min(m_{ij} - m_{kl}) < 20 \text{ GeV} . \quad (10)$$

And finally, ALEPH finds that for this “correct” pairing, slightly more than half (9/16) the events fall within the energy range

$$103.3 \text{ GeV} < \Sigma m (\equiv m_{ij} + m_{kl}) < 106.6 \text{ GeV} . \quad (11)$$

We shall, however, *not* use equation (11) as a cut. For one, the position of this bin might change with accumulation of statistics or a change in the jet merging algorithms. Secondly, it is interesting to see what kind of distributions are predicted within the scenarios that we are about to consider and compare these with the data. This is likely to afford us a better understanding of the operative physics.

If squark mediated decays (eqn. 3) were to be the dominant channel, the final state would comprise of six quarks, on which we must impose the conditions described in eqns (5–10). In Fig. 4a, we exhibit  $\sigma_{\text{eff}}$  (for decays mediated by a virtual stop) as a function of the ratio of the gaugino mass parameters  $M_2/\mu$ . While for small  $M_2/\mu$ , we have relatively large cross sections, for large  $M_2/\mu$ , we are quickly led to a plateau<sup>9</sup> of the order of the central value in eq.(2).

The *efficiency* obviously depends on the mass of the top-squark, and the difference arises from different kinematical sources. The role of the various effects can be seen from a study of the table in Fig. 5a, wherein we have tabulated the effective cross section after each of the cuts mentioned in eqs.(5–11).

One may question our explanation from the point of view that this particular decay mode involves a  $b$ -quark. For example, if we do demand that the observed jets carry *at most one b* ( *i.e.*, at least one  $b$  leads to a ghost jet), we get a much smaller cross section

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<sup>8</sup>One might argue against applying such algorithms to *partons* and propose the cone algorithm (see eq.(12)). We have made the comparison and while the efficiencies do change, the gross features of our analysis remain unaltered.

<sup>9</sup>We have not included here the small contribution from the direct production of a 52 GeV squark.

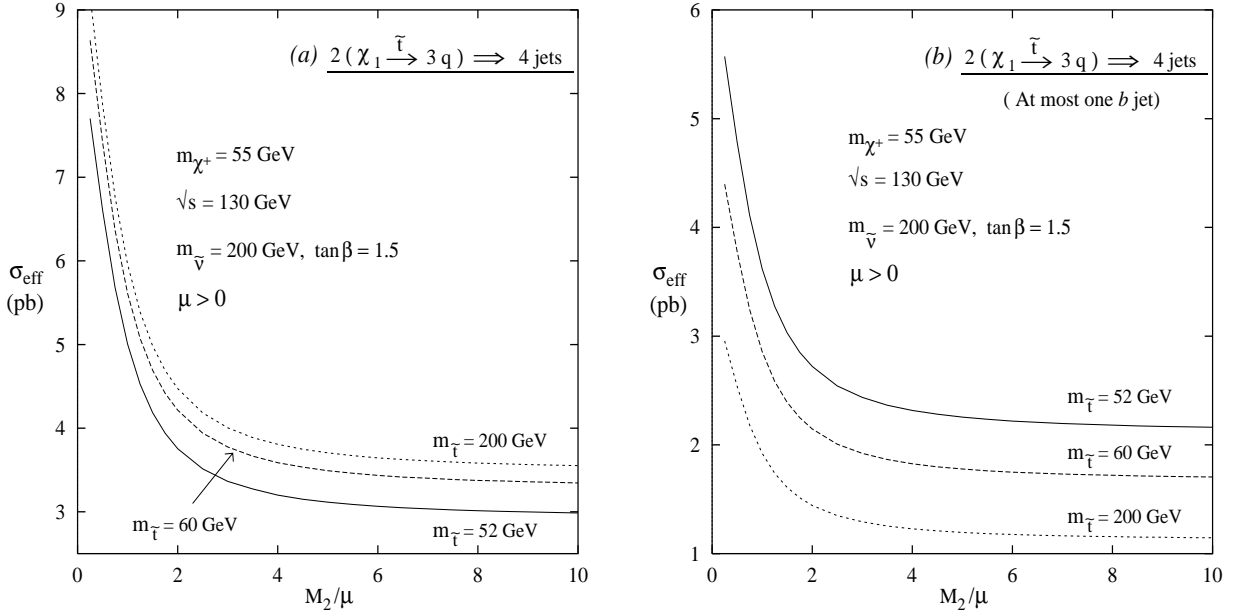


Figure 4: (a) Typical effective (*i.e.* after the imposition of the cuts of eqs.(5–10)) 4–jet cross section for pair–produced charginos decaying solely through the stop channel (see eqn.3). (b) As in (a), but with the additional constraint that at most one  $b$ -quark may contribute to the visible energy.

(see Fig.4b). The difference thus constitutes the sample where *both* the  $b$ -jets are visible (though often merged with light quark jets). Thus, although ALEPH has a strong negative result only for the  $b\bar{b}b\bar{b}$  mode and the bounds on the relative abundance of  $b\bar{b}q_1\bar{q}_2$  channel are less precise, this still seems to constitute a potential problem for the scenario, especially for larger  $m_{\tilde{t}}$ .

There is still another issue that we have not addressed as yet. Does the  $\mathcal{R}_p$ - induced 4-jet sample fall primarily within the  $103.3 \text{ GeV} < \Sigma m < 106.6 \text{ GeV}$  window? A look at the table in Fig.5a and Fig.6b convinces us that this is not so. While an efficiency factor of 55% would have nearly mirrored the ALEPH data, we have a considerably lower fraction (about 10-20%) populating this bin. The cause is not difficult to see. The chargino decay is a genuine three-body one leading to six quarks in the final state. Though these do merge, often it is not the right combination that merge. Consequently, the invariant mass pairing would often choose the wrong combinations. Thus, this additional cut would shift the curves of Fig.4 much too low to explain the observed events.

Let us now explore the possibility that  $m_{\tilde{t}}$  is small enough so that the chargino can decay into an on-shell stop and a  $b$ -quark. Since LEP already provides lower limits on  $m_{\tilde{t}}$ , we immediately see that the  $b$  quark will, almost always, be very soft. In fact, it would never survive the cuts of eq.(5) and would be lost to the detectors. (In fact, a comparison of the  $m_{\tilde{t}}$  dependence in Fig.4a and Fig.4b already points to this.) All visible

Cut	$\sigma_{\text{eff}}$ (pb)	
	$m_{\tilde{t}} = 200$ GeV	$m_{\tilde{t}} = 60$ GeV
None	8.94	8.94
$E(\text{jet}), \eta(\text{jet})$	8.60	8.58
$E_{\text{miss}}$	8.60	8.55
$y$ -cuts	7.87	7.65
$m_{ij} > 25$ GeV	4.73	4.42
$\Delta m$	4.47	4.21
$\sum m$	0.62	0.61

(a)  $m_{\chi^+} = 55$  GeV,  $\tan\beta = 1.5$ ,  $m_{\tilde{\nu}} = 200$  GeV

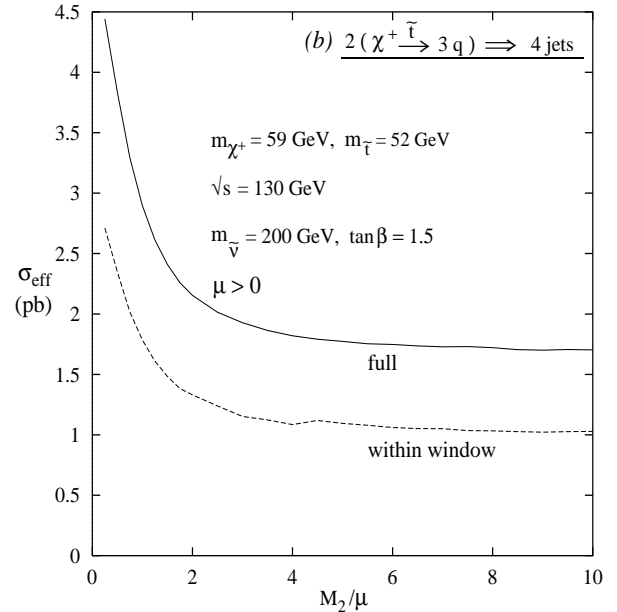


Figure 5: (a) The effective cross-section, on imposition of various cuts, for two typical values of the stop-mass. The efficiencies are independent of  $M_2/\mu$  which has been chosen to be 2.0. (b) The effective cross-section for a 59 GeV chargino and 52 GeV stop. The lower(upper) curves are with(out) the cut of eqn.(11). There are no  $b$  events.

energy would now originate from the decay of the stops into a pair of quarks each. Pairing mismatch effects are small, and hence most of the events could be expected to fall within the  $103.3 \text{ GeV} < \sum m < 106.6 \text{ GeV}$  window. Of course, to match with the ALEPH data, it is now  $m_{\tilde{t}}$  which is to be in the (51 – 54) GeV range, with the chargino heavier by about 5–12 GeV. In Fig. 5b, we exhibit the situation for a particular mass combination<sup>10</sup>. It should be noted that we have not folded in the actual  $Br(\chi^+ \rightarrow \tilde{t} \bar{b})$ , but have assumed it to be 100% (as stressed earlier, in the considered case this assumption is correct within about 10% uncertainty).

For such a combination, both the  $\Delta m$  and  $\sum m$  distributions (see Fig.6) turn out to be very close to the observed signal. While the table in Fig.5a already tells us an agreement in the  $\Delta m$  is quite general, the  $\sum m$  agreement is crucially dependent upon such a hierarchy. This, thus, offers a potentially simultaneous explanation of both ALEPH events and large value of  $R_b$ . Such mass combinations are unique in our discussion in the sense of avoiding  $b$ -jets as well as satisfying the distribution of (11).

It is instructive to compare Fig.5b with the curves for  $m_{\tilde{t}} = 52$  GeV in Fig.4. The crucial difference is the difference in the chargino and stop masses. In the former case, the chargino clearly decays into a *real* stop, thus allowing the  $b$ -quark only a very limited phase

<sup>10</sup>We have again neglected the direct production of a stop-pair, as the corresponding total cross section is small.

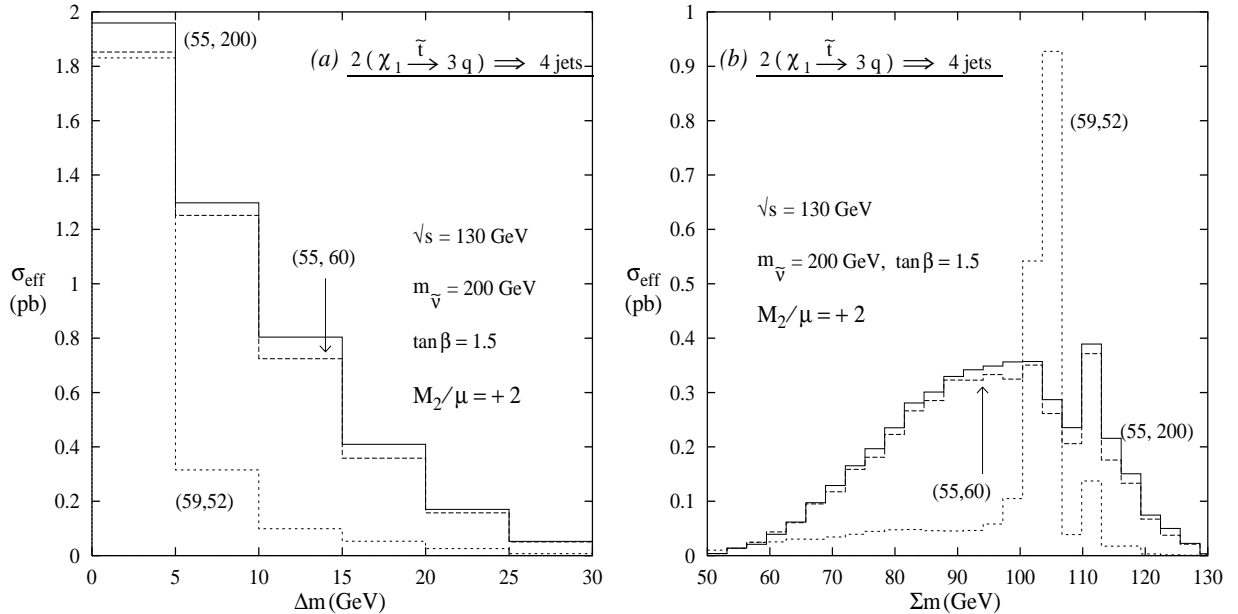


Figure 6: (a) The variation of the effective cross-section with  $\Delta m$  on imposition of the cuts of eqs.(5–9). The numbers in the parentheses refer to the chargino and stop masses respectively. (b) As in (a), but variation with  $\Sigma m$  instead.

space. As the mass difference shrinks, the stop is pushed towards virtuality and more and more of the  $bs$  begin to acquire larger momenta. The point at which this effect takes over is of course determined by the stop decay width and hence on the magnitude of  $\lambda''_{t ds}$ .

Finally there is one more interesting remark to be made. Had we considered a different squark above, the results would have been similar. Moreover, we avoid problems with  $b$  quarks and can easily explain the magnitude of the cross section observed at ALEPH. Of course, there are also less satisfactory aspects now. For one,  $\tilde{t}_R$  is expected to be the lightest squark both from the point of view of the renormalization group evolution as well as considerations of  $R_b$ . Also,  $\mathcal{R}_p$  couplings such as  $\lambda''_{t ds}$  are very weakly constrained and thus may be large enough for the chargino decay to be dominated by stop exchange. Nor should it be forgotten that requiring a sharp  $\Sigma m$  distribution would then necessitate the squark to be almost degenerate with the chargino (since the quark at the primary decay vertex is now very light).

We now move on to the decay channel of eq. (4). At this point, two comments are in order:

- We assume that  $\chi_1^0$  is lighter than  $\chi^+$ . To be specific, we make the assumption of universal gaugino masses at the unification scale. The latter would thus prefer to decay into an on-shell  $\chi_1^0$  and a pair of fermions. Since the mass splitting between  $\chi^+$  and  $\chi_1^0$  is a function of  $M_2/\mu$  (see Fig. 7a), one envisions an additional

dependence on this ratio (on account of the kinematical distribution of the decay particles) over and above the dependence through the production cross section.

- If  $\lambda''_{tds}$  were the only non-zero  $\mathcal{R}_p$  coupling,  $\chi_1^0$  would have a 5 body decay rather than a 3 body one. The final state will thus have 14 particles in it. To simplify the discussion as well as to keep our simulations at a tractable level, we rather consider a scenario where some other coupling (such as  $\lambda''_{cds}$ ) is non-zero instead and one of the associated squarks is the lightest. This choice is somewhat unaesthetic<sup>11</sup> but, hopefully, gives us qualitatively similar results to the 5-body decay.

The final state can then be one of three:  $10q$ ,  $8q + l\nu$  and  $6q + ll'\nu\nu'$  with relative fractions close to  $4 : 4 : 1$ . We consider first the purely hadronic decay channel.

The large event multiplicity, at the parton level, may lead one to suspect that most of the events would actually lead to more than 5 jets. However, the very multiplicity leads to many of the quarks being either soft or close to each other. The same combination of phase space cuts and jet merging algorithm, as discussed earlier, then forces a large fraction of the possible final states to merge into  $4/5$  jets.

In Fig.7b, we display the effective cross section for this mode as a function of  $M_2/\mu$ . The effective cross sections are significantly lower than those obtained for the squark mediated decay. Even more striking is the difference in the  $M_2/\mu$  dependence. Comparing these curves with that of Fig.3b, we see that the efficiency is the least for comparatively lower values of  $M_2/\mu$ . The reason is not difficult to understand. For smaller values of this ratio, the neutralino is significantly lighter than the chargino (see Fig.7a) and thus the quarks from the primary decay vertex are, on the average, quite energetic. Drawing on the experience of the stop-mediated decay, one immediately envisages the rather large probability of wrong merging and pairing of jets. This feature is likely to survive for 5-body decays of the neutralino as well.

Accommodating  $M_2/\mu \lesssim 25$  (in a scenario with gaugino mass unification) is difficult on two accounts. A small value for this leads to configurations where all the quarks are quite energetic. Consequently, a larger fraction of events end up with *more than 5 jets*. As ALEPH has not reported events with such large multiplicity, the scenario stands on a weak ground. Also, note that  $\chi_1 \rightarrow \chi_1^0 f f'$  decay has only 67% hadronic branching fraction. Thus we should have expected to see quite a few events with 3 or 4 jets and an isolated energetic lepton (possibly with significant missing momentum as well). We have simulated such decay modes with the requirement that the isolated lepton carries a minimum of 10 GeV. To quantify isolation, we use

$$\Delta R \equiv [(\Delta\phi)^2 + (\Delta\eta)^2]^{1/2} \quad (12)$$

where  $\Delta\phi$  and  $\Delta\eta$  represent respectively the azimuthal separation between the lepton and a jet and the difference in their rapidities. Choosing  $\Delta R = 0.5$ , we find that, for

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<sup>11</sup>Strictly speaking, in the presence of the baryon number violating couplings, the lower mass bound on right handed squarks of the first two generations are around 45 GeV. Nevertheless, as mentioned earlier, one expects the stop to be the lightest squark.

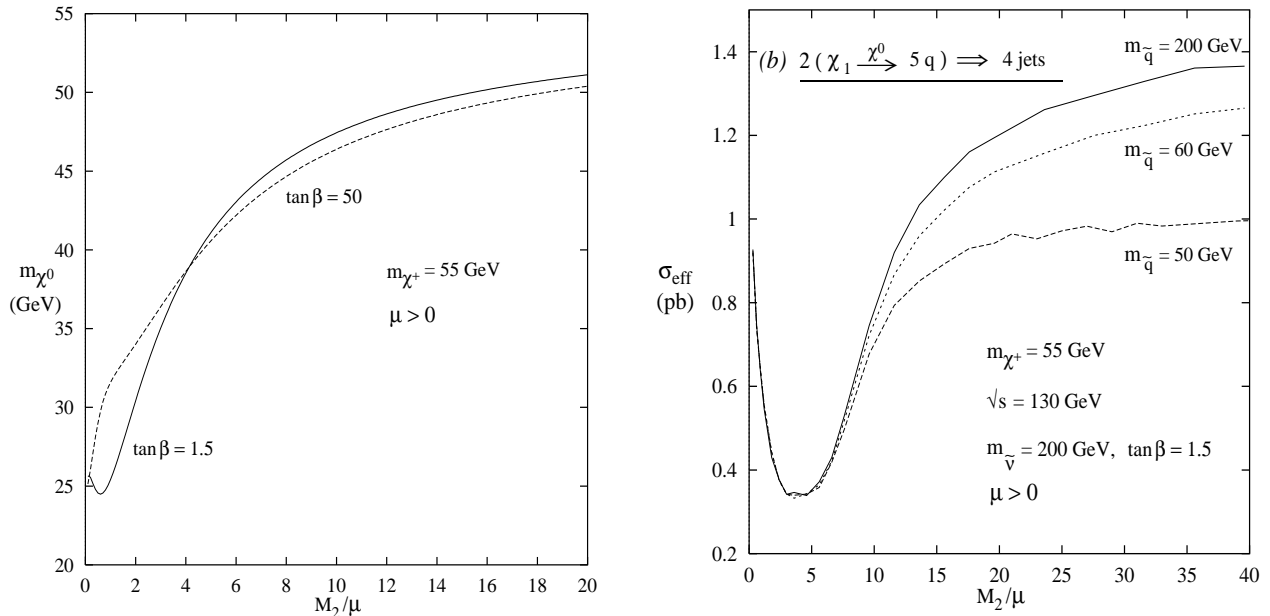
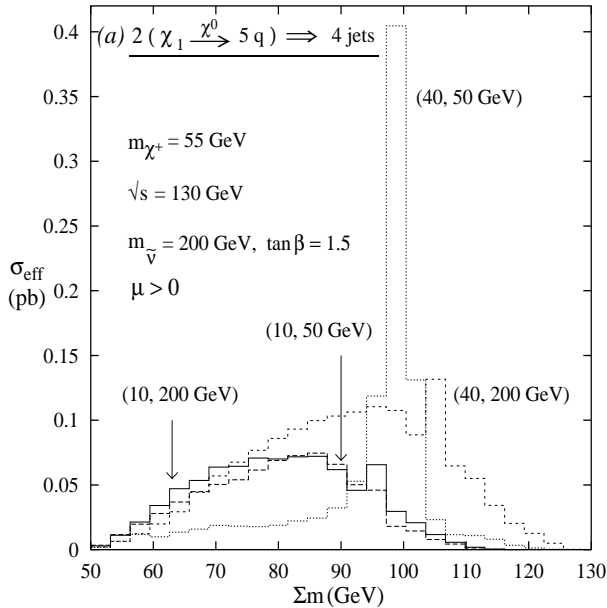


Figure 7: (a) *The lightest neutralino mass as a function of  $M_2/\mu$  for fixed chargino mass of 55 GeV. Gaugino mass unification has been assumed.* (b) *Typical effective (i.e. after the imposition of the cuts of eqns.(5–10)) 4–jet cross section for pair–produced charginos decaying solely through the neutralino channel (see eqn.4)*

the parameter space of interest, at most 3 events with (3 jets + isolated lepton) and 2 events with (4 jets + isolated lepton) are expected. The SM backgrounds arise from both QCD processes and  $b\bar{b}$  production. No such excess have been reported as yet. While it may be still too early to rule out this possibility, it would, perhaps, be better if a proposed scenario does not lead to such events. This can be ensured only the chargino and the neutralino are closely degenerate<sup>12</sup>, when the leptons (and the neutrinos) would again be very soft and hence not meet the selection criteria.

A close degeneracy is “useful” on another account too. As in heavy stop mediated decays, here too we expect the mass distribution to be relatively broad. That this is indeed the case is borne out by a look at Fig.8a. Only when the chargino and the neutralino are almost degenerate, and hence the primary decay quarks are soft to be observed, can we have a relatively sharp distribution. Here too a distinction may be made between the heavy squark and the light squark case. Since a large  $M_2/\mu$  essentially means that the chargino serves only to increase the neutralino production cross section and that we may instead focus on the decays of the latter, for such a scenario we can borrow the results of the previous section with the chargino replaced by the neutralino. Thus for a squark just

<sup>12</sup>This requires either a very large  $M_2/\mu$  (as in our case) or a relaxation of the gaugino mass unification assumption (the latter, as discussed earlier, also leads to a better fit to the precision data).



Cut	$\sigma_{\text{eff}}$ (pb)			
	$M_2/\mu = 3.0$		$M_2/\mu = 30.0$	
	(200 GeV)	(50 GeV)	(200 GeV)	(50 GeV)
None	8.00	8.00	6.99	6.99
$E(\text{jet}), \eta(\text{jet})$	3.54	3.53	2.94	2.98
$E_{\text{miss}}$	1.24	1.26	2.89	2.97
$y$ -cuts	0.81	0.81	2.18	1.71
$m_{ij} > 25$ GeV	0.35	0.38	1.37	1.06
$\Delta m$	0.34	0.34	1.31	0.98
$\Sigma m$	0.013	0.012	0.36	0.11

(b)  $m_{\chi^+} = 55$  GeV,  $\tan \beta = 1.5$ ,  $m_{\tilde{v}} = 200$  GeV

Figure 8: (a) The  $\Sigma m$  dependence of the effective cross section, for various  $(M_2/\mu, m_{\tilde{q}})$  pairs. All cuts except that of eqn. (11) have been imposed. (b) As in Fig.5a, but for the neutralino-dominated decay channel. The numbers in the parentheses represent the relevant squark mass.

about lighter than the neutralino<sup>13</sup>, the quark from the primary (neutralino) decay vertex would be soft (unobservable) and thus effectively we return to squark pair-production (albeit with enhanced cross section), with each decaying subsequently to a pair of quarks. The squark mass dependence can be inferred from the table in Fig.8b.

We may then safely infer that if the  $\chi_1^+ \rightarrow \chi_1^0 f f'$  decay mode is to be the dominant one, then a satisfactory explanation of the ALEPH events necessitates both a close degeneracy between the chargino and neutralino masses, and a squark just about lighter than the neutralino. Clearly, a scenario with the chargino decaying directly into a such a light squark is more attractive.

To conclude, we point out that broken  $R$ -parity (specifically the existence of the baryon number-violating  $\lambda''$  couplings) could provide an explanation for the excess four-jet events observed by the ALEPH collaboration. Though several mechanisms have already been proposed [10, 25], the scenarios therein are in considerable disagreement with the global fits. We instead focus on a light chargino, which subsequently decays into 3 (stop-mediated) or 5 (neutralino mediated) quarks each. Parton level simulation show that, for a considerable fraction of the events, the resultant jets merge to give a signal similar to that observed by ALEPH. While this is true for a large region of the parameter space, a

<sup>13</sup>Though in this case, the chargino will tend to decay directly into this squark (unless it is a  $\tilde{b}$ ), we neglect this effect for the time being.

close agreement with the observed (albeit with low statistics) invariant mass distribution is possible only for a more restrictive set. The best fits are obtained for a chargino decaying predominantly into a stop-bottom pair, with the extremely soft  $b$  escaping detection and the stop ( $\sim 52$  GeV) decaying into a pair of quarks. It is interesting to note that, for such a choice of parameters,  $R_b$  can indeed be significantly larger than the SM value.

We must reiterate that our analysis is only a parton level one, and hence our results are at best indicative. A more definitive statement would require a proper simulation including, amongst others, hadronization effects and detector efficiencies. What lends additional credence to our parton level analysis is a comparison (for some of the stop-mediated decay modes) with a full Monte Carlo analysis with quark fragmentation in JETSET and a simulation of the ALEPH detector. The simple parton-level and the complete analyses agree at the 15% level in both the accepted number of events and the shape [26].

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*Note added:* The possibility that the 4-jet events can be interpreted in terms of pair-produced charginos (and neutralinos) decaying through the  $\lambda''$  couplings has also been considered in ref.[27]. The authors agree that neutralino production cross sections are too small, and that an explanation in terms of charginos decaying through the neutralino channel, while viable, is tenuous. However, they have not examined the (better) decay mode of eq.(3). Also, the connection with  $R_b$  has not been explored.



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