Signatures for Squarks in the Light Gaugino Scenario

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When the gluino is light and long lived, missing energy is a poor signature for both squarks and gluinos. Instead, squark pair production leads to events with ≥4 jets. If a chargino can decay to squark and quark, missing energy is also a poor signature for the chargino. Properties of 4-jet events originating from squarks and charginos are discussed. ALEPH's preliminary report of an excess of 4-jet events with a peak in total dijet mass of 109 GeV (not confirmed by other experiments) is analyzed in terms of $S_q S_q^*$ and chargino pair production; concomitant signatures are noted. [S0031-9007(96)00085-3]

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Motivations are accumulating for believing the gluino and photino may be light. This is inevitable in certain scenarios, such as when supersymmetry (SUSY) breaking is transmitted to ordinary particles by the exchange of very heavy ($\sim M$) states, and is not due to gauge singlet vacuum expectation values. In this case gaugino masses and other dimension-3 SUSY-breaking operators are suppressed by a factor M^{-1} compared to squark masses and other dimension-2 SUSY-breaking operators. This has a number of attractive features: (i) There is no SUSY *CP* problem [1]. (ii) Gluino, neutralino, and chargino masses are calculable in terms of μ, $\tan\beta$, and squark and Higgs masses. Given constraints on these parameters, gluino and photino masses are $\lesssim O(1)$ GeV [1]. The mass of the lightest gluino-containing hadron, the gluino-gluon bound state called R^0, is $\sim 1.3-2.2$ GeV [2]. One chargino is lighter than the W, unless $\mu \gtrsim$ few TeV [3]. (iii) With these R^0 and photino masses, the photino relic density is naturally of the correct order of magnitude to account for the dark matter of the Universe [4]. (iv) The R^0 lifetime $\tau(R^0) \gtrsim (10^{-7}-10^{-10})\,(M_{sq}/100\text{ GeV})^4$ sec [1] is long enough that it is unlikely to have been detected in existing searches [2]. (v) An "extra" pseudoscalar is predicted in the flavor singlet meson spectrum at $\sim 1\frac{1}{2}$ GeV; such a state has been observed [2,5]. The papers cited above and references therein treat the phenomenology of light gluino-containing hadrons and strategies for detecting them. Here I focus on the modifications of the squark signature which this scenario implies, as well as the consequent modifications to chargino signatures if these can decay to a squark.

Squarks decay dominantly via $S_q \rightarrow q + \tilde{g}$. A heavy gluino is short lived and promptly produces a weakly interacting neutralino, so that missing energy is a good signature [6]. However, a light gluino hadronizes forming an R^0-containing jet, due to the long lifetime of the R^0 ($>10^{-10}$ sec). When the R^0 finally decays, the energy carried by the photino is so small that missing energy is not a useful signature [7]. Existing collider limits do not apply. [Squarks decay directly to a photino and quark with a branching fraction $Q_{sq}^2\alpha_{\rm em}/\frac{4}{3}\,\alpha_s$. Rescaling the UA(1) and Fermilab Tevatron collider limits to account for this factor of 100 loss in sensitivity produces limits inferior to those discussed below from the Z^0 hadronic width.] In principle, squarks can be reconstructed by pairing jets. However, experience with $W \rightarrow q\overline{q}$ and $t \rightarrow bq\overline{q}$ suggests that at a hadron collider further constraints will be necessary to reduce QCD background, except for very large squark mass. The remainder of this paper is devoted to establishing a search procedure for squarks when their predominant decay is to two or more jets.

Aside from having spin 0 and larger mass, squarks are produced much like quarks. Pair produced squarks generate events containing four or more jets. At an e^+e^- collider, squarks can be pair produced and, above chargino pair production threshold, produced via decay of charginos. If an L squark (say, S_{uL}) or the R stop is lighter than the chargino, major chargino decay modes will be $\chi^+ \rightarrow S_{uL}\overline{d}_L$, $\chi^+ \rightarrow S_{tR}\overline{b}_L$, etc. Note that the best chargino mass limits rely on a missing energy signature; when the branching fraction to such states is reduced by competition from $\chi^\pm \rightarrow S_q q'$, the limits on chargino masses are impaired.

The best limit on squark masses prior to LEP running at 130 GeV, if missing energy is not useful, comes from the determination of the hadronic width of the Z^0. Neglecting quark masses, $\sigma(e^+e^- \rightarrow S_q S_q^*) = \frac{1}{2}\beta^3\sigma(e^+e^- \rightarrow q\overline{q})$ for any given flavor and chirality. Production of a (u_L, u_R, d_L, d_R)-type pair would increase the total hadronic width of the Z^0 by a fraction $(0.06, 0.01, 0.09, 0.003)\beta^3$. The limit on "extra" hadronic width of the Z^0 then limits the mass of squarks. If there are four or more degenerate "light" squarks, their mass must be greater than $\sim M_Z/2$. If only a single flavor of squark is light, this limit is greatly reduced, to $\lesssim 30$ GeV for an L-chiral squark. Masses of R-chiral squarks are quite unconstrained due to their weak coupling to the Z^0. Considering $e^+e^- \rightarrow S_q\overline{q}\tilde{g} + S_q^* q\tilde{g}$ and virtual corrections to $e^+e^- \rightarrow q\overline{q}$ allows the degenerate squark limit to be improved to 50–60 GeV [8]. An analysis with new Z^0 width values and $\alpha_s(Q)$ determined assuming a light gluino is needed.

Consistency between the observed top mass and number of events in conventional signatures requires the mass of at least one stop eigenstate to be $\gtrsim m_t$ since otherwise $t \rightarrow S_t + \tilde{g}$ would be the top's main decay mode. Limits on isospin-violating radiative corrections to precisely measured electroweak parameters can be used to constrain the sbottom-stop splitting [9].

In the recent LEP run at $E_{\mathrm{c.m.}} = 130-136$ GeV, ALEPH found 14 events which meet their 4-jet criteria, when 7.1 events are expected from standard model physics and less than one 4-jet event is expected from either hA or H^+H^- production. (L. Rolandi, Joint CERN Particle Physics Seminar on First Results from LEP 1.5, 1995.) Furthermore, 8 of these 4-jet events have a total dijet mass of $\sim$109 GeV. No significant excess of such events has been reported by other LEP experiments. Approximating the statistical error associated with 7 events by $\pm\sqrt{7}$, the ALEPH data give $R_{\geq 4} = 2.0 \pm 0.4$. If the 7 event excess is averaged over all four LEP experiments, assuming equal sensitivity and no excess in other experiments, $R_{\geq 4} = 1.25 \pm 0.1$. We will see below that such events have a natural interpretation in terms of squark production. The ALEPH excess may prove ephemeral, so the characteristics of squarks discussed below are applicable in any squark search.

The most striking feature of squark pair production is the excess number of events with 4 or more jets. Define the fraction of ordinary events with four or more jets, for a given energy and jet-finding algorithm, to be $f_{\geq 4}$. In ALEPH's analysis, $f_{\geq 4} = 0.1$. Squark pair production can be a small fraction of the total e^+e^- cross section and yet make a large perturbation on the number of 4-jet events because $f_{\geq 4}$ is small. The ratio, denoted $R_{\geq 4}$, of the actual number of $n_{\mathrm{jet}} \geq 4$ events to the number expected in the standard model is shown in Fig. 1 for the illustrative case (called dls) of degenerate u, d, s, c squarks, as a function of their mass, for $E = 133$ and 190 GeV. A LEP measurement of $R_{\geq 4} = 1.25-2.4$ at $E_{\mathrm{c.m.}} = 133$ GeV implies in the dls case a common squark mass in the range 54–62 GeV. This is consistent with the 109 GeV peak in the total dijet mass distribution reported by ALEPH. The dotted curve in Fig. 2 shows the energy dependence of $R_{\geq 4}$ for 55 GeV dls squarks.

An $\sim$55 GeV chargino and slightly lighter squark can also account for the rate of excess 4-jet events and the peak in total dijet invariant mass reported by ALEPH. From a parton point of view, the chargino cascade mechanism produces 6-jet and not 4-jet events. However, when the chargino-squark mass difference is small, the energy of each primary quark jet (q' in $\chi \rightarrow S_q q'$) is too low for it to be distinguished as a separate jet and the particles of the soft primary jets are associated to the hard jets of the event, producing 4-jet events. Furthermore, the ALEPH analysis procedure merged jets in order to have no more than 4 jets.

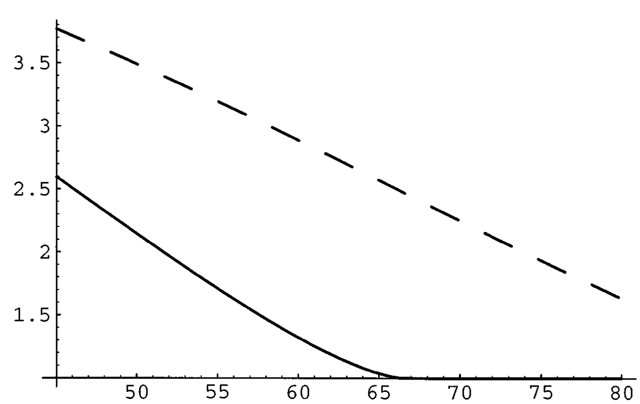

FIG. 1. $R_{\geq 4}$ for degenerate u, d, s, c squarks as a function of their mass in GeV. Solid (dashed) curve is for $E_{\mathrm{c.m.}} =$ 133 (190) GeV.

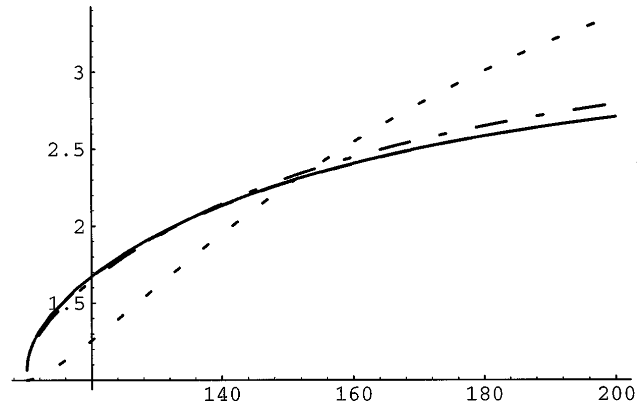

FIG. 2. $R_{\geq 4}$ as a function of $E_{\mathrm{c.m.}}$ for a 55 GeV chargino with $\tan\beta = 1$ (solid) and 1.8 (dash-dotted), and for 55 GeV dlsquarks (dotted) curves.

In order to account for a peaking of the dijet total mass at 109 GeV, the lighter chargino mass must be around 55 GeV. Without tree-level gaugino masses, the masses and mixings of the charginos and their production cross section depend only on μ and $\tan\beta$. The range of μ and $\tan\beta$ corresponding to a given chargino mass is quite restricted: e.g., for $m(\chi^{\pm}) = 55$ [65] GeV, $\tan\beta$ ranges from 1 at the maximum allowed value of μ (62 [34] GeV) to 1.8 [1.4] when $\mu = 0$. (In the minimal supersymmetric standard model such small $\tan\beta$ can conflict with Higgs mass bounds; however, additional scalars are expected in most models and this is not a generic problem.) As for production of any heavy fermion pair, the threshold dependence of the cross section is $\sim\beta(3 - \beta^2)/2$.

The $\geq$4-jet event rate in the chargino cascade mechanism depends also on the branching fraction b for $\chi^{\pm} \rightarrow S_q q'$. Figure 2 shows $R_{\geq 4}$, for a 55 GeV chargino and one 53 GeV L squark, as a function of $E_{\mathrm{c.m.}}$. μ has been fixed by the chargino mass, taking $\tan\beta = 1$ and 1.8; b has been taken 0.45 and 0.50 so that in each case $R_{\geq 4} = 2$ at 133 GeV. b of this order is quite plausible. For example, if a single L squark and three sneutrinos are lower in the mass than the chargino and their phase space differences can be neglected, $b = 1/2$.

Given b, the total branching fraction for $\chi^{\pm} \rightarrow S_\nu l + S_l \nu$ is $(1 - b)$. Letting N_{4j} denote the number of $\geq$4 jet events in the chargino mass peak, N_{2jSl} denote the number of events with one chargino decaying to $S_q q$ and the other to $S_\nu l$ or $S_l \nu$, and N_{SlSl} denote the number of events with both charginos decaying to $S_\nu l$ or $S_l \nu$, we have $N_{4j}:N_{2jSl}:N_{SlSl} = 1:2(1-b)/b:(1-b)^2/b^2$. The main decay mode for S_l and S_ν is likely to be the two body decay to the photino: $S_l \rightarrow l + \tilde{\gamma}$ and $S_\nu \rightarrow \nu + \tilde{\gamma}$. In the example above with only sneutrinos and a squark lighter than the chargino, the $2jSl$ events contain two jets, a very soft charged lepton $[E \sim m(\chi^\pm) - m(S_\nu)]$ and $E_{\text{miss}} \sim m(S_\nu)$. These alternate decay modes should be sought; possibly they can be used to exclude the chargino scenario. However, the reader is cautioned that for the moment the number of events is too small for these productions to be more than indicative of where to look. Averaging over all four LEP experiments gave $R = 1.25 \pm 0.1$; so, interpreting the ALEPH events as a lucky upward fluctuation in the rate and the others as unlucky downward fluctuations, a more realistic value might be $R = 1.45$. With a 58 GeV chargino and a 55 GeV squark, this can be accommodated with $b = 0.35$.

Now let us turn to features of events with $n_{\text{jets}} \geq 4$ which would be indicative of squark production: (i) dijets from direct $S_q S_q^*$ production should have equal masses; (ii) the angular distribution of jet clusters should be $\sim \sin^2\theta$ for squarks and $1 + \cos^2\theta$ for charginos; and (iii) tagging may be possible for the gluino jet.

Gauge interactions (including their SUSY transforms involving gauginos) conserve chirality. The absence of flavor-changing neutral currents implies that gauge interactions of squarks are flavor diagonal to high accuracy, except possibly for stop scharm. Furthermore, the *mixing* between eigenstates of chirality for a given flavor squark is small [$\mu m_q/M_q^2$ times $\cot\beta$ ($\tan\beta$) for charge $2/3$ ($-1/3$) squarks], except possibly for stops. Thus the *dijets from a directly produced squark pair have equal masses when the jets are correctly reconstructed and paired.* This is a crucial point. Since the various squark flavors need not be degenerate, the dijet invariant mass spectrum may be messy, with nearby, overlapping peaks. Nonetheless, even in this situation one has a clear signal since correct pairing of jets leads to a vanishing *difference* of dijet invariant masses. Henceforth jets are always taken to be paired so the dijet mass difference is minimized.

If the squarks are decay products of charginos they need not be identical. However, aside from stops, they would be left-chiral so their splitting is $M_{UL} - M_{DL} = [\cos 2\beta(1 - \sin^2\theta_W)M_{Z^0}^2 + m_U^2 - m_D^2]/(M_{UL} + M_{DL})$ at the SUSY breaking scale.

Spin-0 and spin-1/2 particles produced in e^+e^- scattering through the spin one photon or Z^0 have a $\sin^2\theta$ and $1 + \cos^2\theta$ angular distribution, respectively. If the events with total dijet mass $\sim$109 GeV were due to the decay of directly produced squark or chargino pairs and the decay partons were perfectly reconstructed, taking these events alone should produce one of these angular distributions.

Unfortunately, near the threshold it is difficult to reconstruct the primary quarks and gluinos from the observed hadrons. This means the angular distribution and invariant mass difference of the primary squarks or charginos are poorly determined. ALEPH modeled the distribution of dijet mass difference at $E_{\text{c.m.}} = 135$ GeV resulting from two 55 GeV particles each decaying to $q\overline{q}$ and found the peak in reconstructed dijet mass difference to be $\sim$15 GeV FWHM. Requiring the minimum dijet mass difference to be less than 20 GeV only reduced the number of events expected in the standard model from 8.6 to 7.1. Thus while the data are consistent with equal mass squarks, this is not a very stringent test of the hypothesis. Fortunately, the situation improves as $E_{\text{c.m.}}$ is increased. When the jets from chargino or squark decay are collimated by a Lorentz boost, the ambiguity of associating observed hadrons with the correct primary is reduced. Then the invariant mass and angular distribution of the primaries can be better determined and the cuts to remove background can be tightened.

If both direct and cascade production of squarks are important and the squark and charginos are close in mass, the event properties near chargino threshold are complicated. The particles of the soft primary quark jets in chargino decays would be associated in a more-or-less random way with the 4 hard jets. This would tend to broaden the dijet invariant mass distribution compared to direct squark pair production, although the average invariant mass of the dijet remains centered on the chargino mass, to leading approximation. The ALEPH cut $\min(m_i + m_j) > 10$ GeV removed 5 events from the Monte Carlo calculation of the SM prediction, but only 2 events from the data. This may be a hint of chargino cascade, because when the particles of the very soft primary quark jets are associated with the 4 hard jets, the invariant mass of the resultant jets increases.

Squarks are pair produced in approximate flavor eigenstates so that $S_q S_q^*$ events should contain 2 gluino jets and 2 jets of the same flavor, e.g., b and $\overline{b}$ or c and $\overline{c}$. There will often be additional gluon jets since with typical jet definitions (e.g., $y_{\text{cut}} = 0.01$), 40% of the hadronic Z^0 decays have $\geq$3-jet final states. The hadronization of gluino jets will nearly always produce an R^0 [2] which ultimately decays to a photino which escapes. R^0 tagging may allow confirmation of the $S_q S_q^*$ origin of an excess of $\geq$4-jet events. The R^0's decay to a photino and a small number of pions [1]. The photino typically has a momentum transverse to the R^0 direction of $\sim$0.4–0.8 GeV [1], depending on the relative mass of R^0 and $\tilde{\gamma}$. The average momentum fraction x_R of an R^0 with respect to its jet can be determined in a Monte Carlo or other model of jet fragmentation, or taken by analogy from, say, charm fragmentation. If the lifetime of the R^0 is short compared to the transit time of the calorimeter and its decay is two body, the photino momentum along the jet ranges up to $x_R M_{sq}/2$. On the other hand, if the R^0 lifetime were long enough that it loses it kinetic energy in the calorimeter before decaying, the momentum carried away by the photino would be small, and distinguishing a gluino jet from a gluon jet would be difficult.

As can be seen from Fig. 2, with improved statistics and higher energy, LEP measurement of $R_{\geq 4}$ will provide a powerful tool to support or exclude the hypothesis that squarks are being produced. The threshold behavior clearly distinguishes cascade and direct production. The threshold for chargino production is well defined and the chargino mass inferred from it should agree with the peak in "dijet" (really, $\geq$3-jet cluster) mass.

If a chargino with mass less than m_W is eventually excluded, SUSY breaking which does not produce tree-level gaugino masses will be ruled out unless μ is much larger than has been considered plausible up to now [3]. If, on the other hand, a chargino is found below the W, the search for squarks in $\geq$4-jet events should be pursued at higher energy. The range of LEP can be extended somewhat by allowing one member of the squark pair to be off shell. Then only one pair of jets will reconstruct to a definite invariant mass.

At a hadron collider the background to the multijet signal is more severe. Chargino pair production is parametrically smaller than squark pair production by a factor of $\sim\alpha_w/\alpha_s$. (See [11] for a discussion of associated squark-gluino production.) With good resolution, a peak should be found in the mass difference of dijet pairs, and the flavor one jet of each pair should be the same. At a cost of a factor of $Q_{sq}^2\alpha_{\rm em}/\frac{4}{3}\alpha_s \sim 100$ in rate, one could trigger on events in which a squark decays to quark and photino. This produces events with missing energy, 1 dijet and 1 or more additional jets.

Although cascade production via charginos would account for only a fraction of squark production in hadron collisions, such events might be more readily identified. If there is a 55 GeV chargino, the tree-level mass of the heavier chargino ($\chi_2^\pm$) falls in the range 99–117 GeV, depending on μ and $\tan\beta$. Important final states in its decay are $W^\pm + \chi^0$, $\gamma + \chi_1^\pm$, $S_q q$, $S_l \nu$, and $S_\nu l$. $Z^0 + \chi_1^\pm$ is not kinematically allowed because $m(\chi_2^\pm) - m(\chi_1^\pm) < m(Z^0)$. Thus this scenario predicts events with W or γ, but not Z^0, recoiling against "dijet" (actually $\geq$3-jet) clusters with an invariant mass peak at the mass of the heavier chargino, at a level possibly observable at the Tevatron. Events with other striking combinations of chargino decay products are also predicted [10].

In $e^- p$ collisions a produced squark is 4–8 times as likely to be a u squark as a d squark depending on the x regime of the collision: a factor of 4 from the quark charge squared and a factor of $1-2$ from the relative probability that the initial parton is a u vs d quark. Ignoring therefore the production of d squarks, the probability that squark production leads to a prompt photino is 4%. Half the time the photino is associated with a dijet which reconstructs to M_{UL} or M_{UR}; the other half of the time the 2 jets accompanying it have no particular relation as one came from the decaying squark and the other was the primary gluino associated with the squark production.

To recapitulate, the signatures of squarks and charginos have been discussed when SUSY breaking does not produce tree-level gaugino masses or scalar trilinear couplings. In this case a chargino must be lighter than the W and the gluino is light and hadronizes. $\sim$99% of pair-produced squarks produce events with 4 or more jets and little missing energy. If an L squark is lighter than the chargino, a primary decay of the chargino is squark + quark and chargino signatures relying on the decay $\chi^\pm \rightarrow \chi^0 f \bar{f}'$ are diminished in utility. Emphasis was placed on features of events with 4 or more jets which are characteristic of $S_q S_q^*$ production or of chargino production and decay to squarks. Properties of gluino-containing jets which could be helpful in discriminating them from quark or gluon jets are discussed. The energy dependence of events with 4 or more jets is a powerful tool to establish the existence of a signal and to discriminate between cascade and direct squark production.

The excess of 4-jet events reported recently by ALEPH, if confirmed by other experiments and higher statistics, could be circumstantial evidence that at least one L squark or stop has a mass $\lesssim$55 GeV and decays to quark and hadronizing gluino. The number of 4-jet events in the total-dijet-mass peak at 109 GeV is consistent with direct production of two generations of L squarks with mass 55 GeV, or production of a 55 GeV chargino which decays to a squark and quark. In the latter case, events with a pair of jets and decay products of sneutrinos or sleptons are expected, and the mass of the heavier chargino would be in the range 99–117 GeV. Higher energy running at LEP will easily exclude or confirm these possibilities.

A careful study of 4-jet events should be a standard part of squark search techniques until a light, hadronizing gluino has been excluded.

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