New Signature of Squarks

Glennys R. Farrar

Department of Physics and Astronomy
Rutgers University, Piscataway, NJ 08855, USA

Abstract: When the gluino is light and long lived, missing energy is a poor signature for both squarks and gluinos. Instead, $S_q S_q^*$ production in $e^+ e^-$ and $p\bar{p}$ collisions characteristically results in events with $\geq 4$ jets. Methods are proposed for deciding whether an observed excess of 4-jet events is due to $S_q S_q^*$ production. The recent report by ALEPH of observation of 14 4-jet events when 7 were expected is discussed.

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I have recently outlined\[1, 2, 3, 4\] some of the low-energy features of theories in which dimension-3 SUSY breaking operators are highly suppressed. This is the generic situation in several interesting methods of SUSY breaking. Two to four free parameters of the usual minimal supersymmetric standard model (\(A\) and the gaugino masses) vanish at tree level. The elimination of these SUSY breaking operators implies that there is no additional CP violation at \(T=0\) beyond what is already present in the standard model\[2\], avoiding the embarrassing SUSY CP problem. Gauginos are massless at tree level but get calculable masses through radiative corrections from electroweak and top-stop loops. Evaluating these leads to gluino and photino masses less than \(\sim 1\ \text{GeV}\)[1]; the lightest chargino has a mass \(\leq m_W\) and thus should be discovered at LEP II.

The lightest \(R\)-hadron is a gluino-gluon bound state often called \(R^0\). Its mass should be in the range \(\sim 1.2 - 2.2\ \text{GeV}\)[3, 4]. It decays to a photino and hadrons. The photino is an attractive dark matter candidate, having the correct abundance for \(r \equiv m(R^0)/m_\tilde{\gamma}\) in the range \(\sim 1.6 - 2\), compatible with expectations[1]. For \(r\) in this range, \(\tau(R^0) \sim (10^{-7} - 10^{-10})(M_{\tilde{\gamma}}/100\ \text{GeV})^{-4}\) sec, so that the lifetime of the \(R^0\) can be long enough that it would not have been detected in existing searches[4]. Methods to study the \(R^0\) and other \(R\)-hadrons experimentally are given in [2, 3].

Squarks are pair produced in \(e^+e^-\) annihilation with cross section \(\frac{1}{2}\beta^3\) times that of a massless quark of the same flavor and chirality[5]. In a hadron collider they can be produced either in pairs from \(q\bar{q}\) annihilation and gluon-gluon fusion, or singly in association with a gluino or (at the \(\sim 1\%\) level) a photino, in quark-gluon fusion. At an \(e^-p\) collider they are produced singly in association with a gluino or (at the 2\% level) a photino.

Once produced, squarks decay dominantly via \(S_q \rightarrow q + \tilde{g}\). The gluino

\[\text{Although squarks have spin-0, they can be ascribed chirality because supersymmetry associates them with a quark of definite chirality. As discussed below, squark chirality violation is very small in this scenario, except for top-squarks.}\]
hadronizes forming a jet, due to the long lifetime of the $R^0$. This is to be contrasted with the conventional case of a very heavy and thus short lived gluino, for which the photino production is prompt. When the $R^0$ in the gluino jet finally decays, the energy carried by the photino is so small that the conventional missing energy signature is not useful\footnote{Squarks decay directly, thus promptly, to a photino and quark with a branching fraction $Q^\ast_{2q} \alpha_{em}/(4\alpha_s)$. For a charge 2/3 squark this occurs about 2\% of the time, the same factor which appears in the ratio of photino to gluino production in deep inelastic scattering from an up quark. Averaging over the $u$, $d$, $s$, $c$ and $b$ squarks, 1\% of the time a single prompt photino is present in the decay products of a squark pair. Naively rescaling the UA(1) and Tevatron collider limits, to account for this loss in sensitivity, leads to limits much worse than those obtained below from the $Z^0$ hadronic width.}. Existing Tevatron collider limits do not apply. The remainder of this paper is devoted to establishing a search procedure appropriate to this scenario.

The best limit on squark masses prior to LEP 1.5, if missing energy is not useful, comes from the determination of the hadronic width of the $Z^0$. In $e^+e^-$ collisions, $\sigma(e^+e^- \rightarrow S_q S^\ast_q) = \frac{1}{2}\beta^3 \sigma(e^+e^- \rightarrow q\bar{q})$ neglecting quark mass, for any given flavor and chirality. Therefore production of a $(u_L, u_R, d_L, d_R)$-type squark antisquark 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 five degenerate “light” squarks (called the dls case below), their mass must be greater than $\sim M_Z/2$. If only a single flavor of squark is light, this limit is greatly reduced. Considering $e^+e^- \rightarrow S_q \bar{q}\bar{g} + S^\ast_q qg$ and virtual corrections to $e^+e^- \rightarrow q\bar{q}$ allows the dls limit to be improved to $50 – 60$ GeV\footnote{\cite{7, 8}}. The analysis should be redone with new $Z^0$ width values and careful treatment of the value of $\alpha_s(M_Z)$ and its running to lower scales, assuming a light gluino, since the expected $Z^0$ width is sensitive to this.

For squark masses up to $\sim \frac{1}{2}E_{\text{LEP}}$, $S_q S^\ast_q$ pairs can be readily produced and identified at LEP. At larger masses, the Tevatron collider complements LEP. In both cases one studies events with four or more jets, as discussed
below. QCD background is much more severe at the hadron collider, but
the signal-to-noise may actually improve with increasing squark mass. The
signature of squarks appears to be less distinctive at HERA, but the fact
that only $u$ and $d$ squarks are produced, so the prompt photino fraction is
enhanced, means that if squarks are found HERA can give complementary
information to the other machines. In the following I will concentrate on $S_qS^*_q$
production at LEP, with the obvious parallels to the Tevatron and HERA
searches left implicit.

In $e^+e^-$ collisions at the $Z^0$ and above, about 10% of hadronic events are
observed to consist of four or more jets, defining jets with $y_{\text{cut}} = 0.01$. Since
especially every $S_qS^*_q$ pair produces four or more jets, a large enhancement
of four-jet events is expected when one is sufficiently above threshold that
the $\beta^2$ suppression is not severe. To be more quantitative, define $f_{\geq 4}$ to be
the fraction of ordinary events with four or more jets for a given energy and
jet-finding algorithm, and

$$r_i(m_i, E) \equiv \frac{\sigma(e^+e^- \rightarrow S^i_qS^{i*}_q)}{\sum_i \sigma(e^+e^- \rightarrow q_i\bar{q}_i)}.$$

Then the ratio of the number of $n_{\text{jet}} \geq 4$ events with and without squarks is
$R_{\geq 4}(E) = \frac{\sum_i r_i(m_i, E) + 1}{\sum_i f_{\geq 4}}$. To show how large an effect squarks produce, Fig.
plots $R_{\geq 4}(m, E)$ for $E = 135$ and 190 GeV, for degenerate $u$, $d$, $s$, $c$, $b$
squark (dls) masses. It should be stressed that other constraints such as the
$\rho$ parameter and Tevatron top quark studies exclude a too-light sbottom and
stop, so the dls case is not realistic.

In the recent LEP 1.5 run at $E_{\text{cm}} = 130 - 140$ GeV, ALEPH$^5$ found 14

$^4$Since the gluino here is light, unless the stop is approximately degenerate with the top
or heavier, the main decay mode of the top would be $t \rightarrow S_t + \tilde{g}$ which is excluded by the
consistency between the observed top mass and the rate of its observation in conventional
signatures. The sbottom mass must be $> \sim \frac{3}{4}$ the stop mass in order not to produce too
large a change in the $\rho$ parameter.

$^5$L. Rolandi, Joint CERN Particle Physics Seminar on First Results from LEP 1.5, Dec.
11, 1995
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. With dls, this rate of 4-jet events implies a 55
GeV common squark mass, as can be seen from Fig. 1. Note that $R$-squarks
decouple at this energy because the photon and $Z^0$ contributions just cancel.
Thus only $L$-squarks are probed at this particular energy. Furthermore, at
this energy $U$- and $D$- type squarks are produced equally, if they have the
same $\beta^3$ factor, making it easy to rescale from the unrealistic dls case.

In view of the various constraints which limit the number of light squarks,
and exclude the stop and sbottom being so light, possibly the most plausible
explanation of the ALEPH events, if they are real, would be a “cocktail” of
pair production of a couple of flavors of squarks with 55 GeV masses and
pair production of a slightly heavier chargino. In the no-dimension-3-SUSY
breaking scenario, one chargino must be lighter than the $W$, so this is a
natural possibility if there are such light squarks. In this case the dominant
chargino decay mode would be $\chi^\pm \to S_q\bar{q} + S^*_q\bar{q}$, assuming the sneutrinos
are heavier. If such a decay channel is available, the branching ratio of the
charginos to the $f\bar{f}\chi^0$ final state (via a virtual $W$) would be suppressed, so
the chargino would not have shown up in conventional searches. Although
the ultimate final state of such chargino pairs has $\geq 6$ jets, for a small mass
splitting between chargino and squarks the primary quark jets have so little
energy they would not pass the cut for an isolated jet so would present
themselves in much the same way as simple $S_qS^*_q$ production.

Now let us turn to the issue of deciding, given a putative excess of events
with $n_{jets} \geq 4$, whether the excess can be attributed to production of $S_qS^*_q$.
Fortunately for the discussion here, some important characteristics of the
final states originating from $S_qS^*_q$ are the same as for the SUSY-Higgs search
which was the motivation for the ALEPH analysis. Therefore many of the
quantities needed in order to decide whether events are consistent with com-
ing from $S_q S_q^*$ pairs have already been calculated and reported by ALEPH.\textsuperscript{5}

A very important characteristic of squark pair production is that the squarks produced are degenerate in mass. This is because gauge interactions (including their SUSY-transforms involving gauginos) conserve chirality. Moreover the absence of flavor-changing neutral currents implies that gauge interactions of squarks are flavor-diagonal to high accuracy. Thus when a squark and antischark pair is produced in $e^+e^-$ or hadron colliders, their flavor and chirality are the same. Furthermore, the mixing between eigenstates of chirality for a given flavor squark is small in this scenario, except for the stops\textsuperscript{6}. Thus except for stop pairs, the correct pairing of jets from decays of a squark pair will produce equal mass dijets. 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 or enhancements. Nonetheless, a clear signal is possible since correct pairing of jets always leads to a vanishing difference of the dijet invariant masses. Henceforth jets are always taken to be paired so the dijet mass difference is minimized.

Out of the 14 ALEPH events, 8 have a total dijet mass centered on 109 GeV, with a spread $\sim 10$ GeV consistent with resolution. All eight of these events have a dijet mass difference compatible with zero, as will be discussed in the next paragraph. Thus these 8 events are candidates for originating from pairs of $\sim 54.5$ GeV squarks. This is exactly the squark mass required to account for the observed number of excess events, for the dls case illustrated in Fig. 1.

If it is correct to interpret an excess of events with $n_{jet} \geq 4$ as due to production of approximately degenerate $S_q S_q^*$’s, the excess should be a defi-

\textsuperscript{6}When the effective theory contains only dimension-2 SUSY breaking operators, $A = 0$. Then the mixing $\delta_q$ between chirality eigenstates for squark flavor $q$ is $\delta_q = \frac{\mu m_q}{M_q^2}$ times $\cot\beta$ $(\tan\beta)$ for charge $2/3$ (-1/3) squarks respectively; $M_q$ is the average mass of the squarks of flavor $q$. 

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nite function of cm energy. The $r_i$’s of eq. (1) grow as $[1 - (2M_{\text{dijet}}/E_{\text{cm}})^2]^{3/2}$.

Ignoring the variation of $f_{\geq 4}$ with energy, this means that if the ALEPH excess were due to production of degenerate $S_q S_q^*$ pairs, when LEPII runs at 165 (190) GeV the $\geq 4$-jet event rate should be 3.1 (3.7) times the expected rate from standard model processes alone. Thus with improved statistics and higher energy, LEPII measurement of $R_{\geq 4}$ will provide a powerful tool to support or exclude the hypothesis that squarks are being produced, which then decay to quarks and hadronizing-gluinos.

What more can be done with a given event sample? Unfortunately, the prediction that the squark and antischark are mass degenerate on an event by event basis may not provide a useful identifier for squarks at present energies. For instance, at $E_{\text{cm}} \sim 135$ GeV ALEPH’s resolution in dijet invariant mass is about 20 GeV full-width-at-half-max. Although the distribution in dijet-mass-difference of the 14 ALEPH events is consistent with equal dijet invariant masses, requiring the minimum dijet mass difference to be less than 20 GeV only reduces the number of events expected in the standard model from 8.6 to 7.1.5 This implies that at $E_{\text{cm}} = 135$ GeV, 80% of standard model events have a dijet mass difference less than 20 GeV, when jets are paired so as to minimize the dijet mass difference and their other cuts are satisfied. Hence the dijet invariant mass difference does not at this energy and squark mass provide a useful test as to whether the excess events are $S_q S_q^*$ in origin, let alone provide a discriminant as to which $\sim 7$ events are potentially squarks and which $\sim 7$ are ordinary (mainly $q\bar{q}gg$) events.

However there are other discriminants which can be investigated. Spin-0 particles produced in $e^+e^-$ scattering through a spin one photon or $Z^0$ have a $\sin^2\theta$ angular distribution. After determining the dijet 3-momenta, the angular distribution of the dijets can be formed. If the events with total dijet mass $\sim 109$ GeV were due to the decay of squark pairs, taking these events alone should produce an angular distribution $\sim \sin^2\theta$. The remaining events (presumably comprised of $q\bar{q}gg$) should be produced according to the
standard model and thus have a different characteristic angular dependence. Hopefully the two distributions will prove qualitatively different enough to allow true $S_qS_q^*$ to be distinguished from background. If the situation is more complicated, as in the cocktail mentioned above with charginos and squarks, large statistics will probably be necessary to compare expected and predicted distributions.

Still more detailed investigations of the events can be made. Some of the salient characteristics to explore are:

I. Certain correlations in the jet angular distributions should reflect the fact that the dijets are actually spin-0 particles, which decay to spin-1/2 particles which then form jets.

II. $S_qS_q^*$ events have two gluino jets, one associated with each dijet. On account of their larger color charge, gluino jets may be “fatter” than standard quark jets. The hadronization of gluino jets will nearly always produce an $R_0^0$\cite{footnote}. Denote the average momentum fraction of an $R_0^0$ with respect to its jet by $x_R$. $x_R$ could be determined in a Monte Carlo or other model of jet fragmentation, or taken by analogy from, say, charm fragmentation. The $R_0^0$’s will decay to a photino and a small number of pions\cite{footnote}. The photino will typically have a momentum transverse to the jet axis of $\sim 0.4 - 0.8$ GeV\cite{footnote}, depending on the relative mass of $R_0^0$ and $\tilde{\gamma}$. If the lifetime of the $R_0^0$ is short compared to the transit time of the calorimeter and its decay is two-body, the photino will typically have a momentum along the jet of $\lesssim x_R \frac{M_{R_0^0}}{2}$. This will lead to characteristic small deviations from the energy and momentum accounting in the event which will show up in appropriate variables. If on the other hand the $R_0^0$ lifetime is long enough that it loses its kinetic energy in the calorimeter before decaying, the momentum along the jet axis carried away by the photino will be nearly imperceptible. A final possibility for “$R_0^0$-tagging” is to look for $\eta$’s, which should be produced with branching fraction $\sim 0.1$ if $R_0^0$ decay is predominantly 2-body\cite{footnote}. Resolution might not be adequate for this, even if enough $\geq 4$-jet events were available.
III. The dominant squark decay channel, $S_q \rightarrow q \tilde{g}$, can produce two jets or bremsstrahlung additional gluons forming $\geq 2$ jets, just as QCD produces $\geq 2$-jet final states in $Z^0 \rightarrow q \bar{q}$ decay. Indeed, a non-negligible fraction of squark final states can be expected to contain $\geq 3$ jets, as in $Z^0$ decay. 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 larger color charge of the gluino is likely to enhance bremsstrahlung compared to a quark jet, although when the squark is significantly lighter than the $Z^0$ this is at least partially compensated by the reduction in phase space which causes jets to coalesce more. These issues should be straightforward to model with minor modifications to event generators such as Pythia and Herwig.

IV. At 133 GeV the production rates for squarks of different flavors is the same, aside from the $\beta^3$ factor which differs if they are not mass degenerate. If the ALEPH excess of events persists when statistics improve and the excess is associated with a single peak in invariant mass, as is consistent with the present small sample, there should be approximately equal numbers of events for each squark flavor produced. When the sbottoms and stops are below threshold, the only $b\bar{b}$ events would be due to standard model final states and $b\bar{b}b\bar{b}$ would be extremely rare.

To summarize: I discussed the events with four or more jets which result from $S_q S_q^*$ production followed by decay to quark and gluino. When SUSY breaking does not produce tree-level gaugino masses or scalar trilinear couplings, the gluino is light and hadronizes so such events are the dominant end product of squark pair production. Methods were given to decide whether an observed 4-jet excess is due to this process. If the excess of 4-jet events reported recently by ALEPH is confirmed by other experiments and higher statistics, it could be circumstantial evidence that some flavors of squarks have mass around 55 GeV. These squarks would be decaying into a quark and gluino which hadronize to two or more jets. This hypothesis is consistent with several features observed in the present small sample:
1. The number of excess 4-jet events, 14 observed when 7.1 were expected, is the number expected with 5 flavors of $L$-squarks having masses $\sim 55$ GeV. In fact, 8 of the 4-jet events do have a total dijet mass of 109 GeV. (But note that other arguments make it unlikely for five squarks to be this light.)

2. The observed peaking at zero dijet mass difference is expected because of the mass-degeneracy of the $S_qS_q^*$ pair for each flavor. (But note that the dijet mass resolution is such that this is not a very stringent test.)

3. The amount of missing energy in each of the events is small – this is as expected because the photinos which are lost are produced after hadronization of the gluino, so they carry very little energy.

4. No $b\bar{b}b\bar{b}$ events are seen; they are not expected in the present scenario because two of the final jets must be gluino jets.

Whether ALEPH has seen a first hint of the production of squarks or squarks and charginos can be investigated further with the existing data. It will be readily confirmed or refuted by more statistics and higher energies. In any case, careful study of 4-jet events should be a standard part of squark search techniques until the time that a light, hadronizing gluino has been excluded.

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Figure 1: Ratio, $R_{\geq 4}$, of the number of events with $n_{\text{jet}} \geq 4$ in the presence and absence of $u, d, s, c, b$ squarks, as a function of the common squark mass in GeV. Solid and dashed curves are for $E_{\text{cm}} = 135$ and 190 GeV, respectively.