CERN-TH.4194/85

SQUARK DECAYS INTO GAUGINOS AT THE $p\bar{p}$ COLLIDER

H. Baer, John Ellis, G.B. Gelmini^{*)}, D.V. Nanopoulos and Xerxes Tata

CERN - Geneva

A B S T R A C T

Conventional analyses of missing p_T events due to squark production at the CERN $p\bar{p}$ collider assume $\tilde{q} \rightarrow q\tilde{\gamma}$ decays dominate. In principle, the monojet and dijet cross-sections could be reduced by competition from $\tilde{q} \rightarrow q\tilde{W}^\pm$ and $\tilde{q} \rightarrow q\tilde{Z}^0$ decays. We compute this reduction factor for two mass scenarios: $m_{\tilde{q}} > m_{\tilde{W}} > m_{\tilde{\gamma}}$ and $m_{\tilde{q}} \approx m_{\tilde{W}} > m_{\tilde{\gamma}}$. The monojet and dijet cross-sections for squarks light enough to be observed in present collider experiments are reduced by no more than 55%, while there may exist an observable cross-section for jet(s) + charged lepton(s) + missing p_T events. Thus the lower bounds on $m_{\tilde{q}}$ usually derived from $\tilde{q} \rightarrow q\tilde{\gamma}$ decays remain valid.

^{*)} Present address: Lyman Laboratory of Physics,
Harvard University, Cambridge, MA 02138,
U.S.A.

CERN-TH.4194/85

June 1985

There is currently considerable interest¹⁾⁻⁵⁾ in searches for supersymmetric particle production at the CERN $p\bar{p}$ collider, and setting either lower or (if we are lucky) upper limits on sparticle masses. Particular interest has been directed towards the pair-production of strongly interacting coloured sparticles - squarks $\tilde{q}$ ¹⁾ or gluinos $\tilde{g}$ ²⁾ - and on $W^\pm$ and Z^0 decays into weakly interacting uncoloured sparticles-sleptons $\tilde{\ell}$ ⁴⁾, winos $\tilde{W}^\pm$ or zinos $\tilde{Z}^0$ ⁵⁾. Rates have been calculated for monojet or dijet + missing p_T ($\cancel{p}_T$) events from $\tilde{g}\tilde{g}$ production, assuming $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$ decays, and from $\tilde{q}\tilde{q}$ production, assuming $m_{\tilde{q}} < m_{\tilde{g}}$ and $\tilde{q} \rightarrow q\tilde{\gamma}$ decays. The few monojet events seen by UA1⁶⁾ have then been used to give lower bounds on the gluino and squark masses. Likewise the few charged lepton(s) + $\cancel{p}_T$ events could be used to give lower limits on $m_{\tilde{\chi}^\pm}$, $m_{\tilde{\nu}}$, $m_{\tilde{W}^\pm}$ and $m_{\tilde{Z}^0}$ ^{4),5)}. In many models $\tilde{q} \rightarrow q\tilde{W}^\pm$ and/or $\tilde{q} \rightarrow q\tilde{Z}^0$ decays are kinematically possible, and it is important to ask whether the quoted lower bounds on $m_{\tilde{g}}$ or $m_{\tilde{q}}$ could be relaxed if $\tilde{g}$ does not decay exclusively into $q\bar{q}\tilde{\gamma}$, or $\tilde{q}$ decay exclusively into $q\tilde{\gamma}$. Moreover, if the winos and zinos are too heavy to be produced via $W \rightarrow \tilde{W}\tilde{Z}$ or $Z \rightarrow \tilde{W}\tilde{W}$, the most copious source of these may well be via squark or gluino decays. The decay $W \rightarrow \tilde{W}\tilde{\gamma}$ is likely to be accessible in a wide variety of models, but this does not lead to as striking a signature as the other decays^{4),7)}.

In this paper, we first present calculations of the $\tilde{q} \rightarrow q\tilde{W}^\pm$, $\tilde{q} \rightarrow q\tilde{Z}^0$ and $\tilde{g} \rightarrow q\bar{q}\tilde{W}^\pm$, $q\bar{q}\tilde{Z}^0$ branching ratios as functions of the sparticle masses. Then we calculate the n jet + m charged lepton + $\cancel{p}_T$ topological cross-sections ($n+m \geq 1$) for different values of the sparticle masses. We find only small cross-sections for events with both jets and charged leptons, and that for $m_{\tilde{q}}$ or $m_{\tilde{g}} \lesssim 80$ GeV the monojet and dijet + $\cancel{p}_T$ cross-sections calculated previously^{1),2)} assuming 100% $\tilde{q} \rightarrow q\tilde{\gamma}$ or $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$ decays are reduced by at most 55% when decays into $\tilde{W}^\pm$ and $\tilde{Z}^0$ are included with the appropriate branching ratios. This is largely because the absence of many charged lepton + $\cancel{p}_T$ events at the CERN $p\bar{p}$ collider already tell us that $m_{\tilde{W}} \gtrsim 40$ GeV⁵⁾, if $m_{\tilde{W}^\pm} > m_{\tilde{\chi}^\pm}$, while unsuccessful searches⁸⁾ for the zino produced via $e^+e^- \rightarrow \tilde{Z}\tilde{\gamma}$ ⁹⁾ tell us $m_{\tilde{Z}^0} \gtrsim 32$ GeV for $m_{\tilde{e}} \lesssim 40$ GeV (corresponding to $m_{\tilde{q}} \lesssim 90$ GeV if $m_{\tilde{q}} \approx m_{\tilde{g}}$ in minimal $N = 1$ supergravity models) so that the phase space for $\tilde{q} \rightarrow q(\tilde{W} \text{ or } \tilde{Z})$ and especially $\tilde{g} \rightarrow q\bar{q}(\tilde{W}^\pm \text{ or } \tilde{Z}^0)$ is correspondingly reduced. Thus the previous calculations of monojet or dijet + $\cancel{p}_T$ signatures for $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$ or $\tilde{g}\tilde{g}$ production which only included $\tilde{\gamma}$ decays remain essentially unaltered, and previously quoted^{1),2)} lower bounds on $m_{\tilde{q}}$ and $m_{\tilde{g}}$ remain valid. Other aspects of squark decays into gauginos may be found in the literature¹⁰⁾.

Figure 1 is intended as a qualitative guide to the discussion in this paper: Fig. 1a is for $m_{\tilde{q}} < m_{\tilde{g}}$, while Fig. 1b is for $m_{\tilde{q}} > m_{\tilde{g}}$. If, in Fig. 1a, $m_{\tilde{W}} > m_{\tilde{q}}$ the previous monojet analysis goes through unchanged: the squark and gluino masses must be greater than $\sim 40 \text{ GeV}^{1),2)}$ and is indicated by the line "UA1". If (A) $m_{\tilde{W}} < m_{\tilde{q}}$, then $\tilde{q} \rightarrow q\tilde{W}^\pm$ decays occur with the rates

$$\Gamma(\tilde{u}_L \rightarrow d + \tilde{W}^+) = \Gamma(\tilde{d}_L \rightarrow u + \tilde{W}^-) = \frac{g^2 f_+^2}{16\pi} m_{\tilde{q}} \left(1 - \frac{m_{\tilde{W}}^2}{m_{\tilde{q}}^2}\right)^2, \quad (1a)$$

$$\Gamma(\tilde{u}_R \rightarrow d + \tilde{W}^+) = \Gamma(\tilde{d}_R \rightarrow u + \tilde{W}^-) = 0, \quad (1b)$$

and, if $m_{\tilde{Z}} < m_{\tilde{q}}$ then $\tilde{q} \rightarrow q\tilde{Z}$ decays occur with the rates

$$\Gamma(\tilde{q}_{L,R} \rightarrow q + \tilde{Z}) = \frac{A_{\tilde{q}_{L,R}}^2}{4} \alpha m_{\tilde{q}} \left(1 - \frac{m_{\tilde{Z}}^2}{m_{\tilde{q}}^2}\right)^2. \quad (1c)$$

Here,

$$\begin{aligned} A_{\tilde{u}_L} &= \frac{N_1 m_Z}{\mu_-} \left(\cot \theta_w - \frac{1}{3} \tan \theta_w \right) - \sqrt{2} \frac{2}{3} \epsilon_1, \\ A_{\tilde{u}_R} &= -\frac{4}{3} \frac{N_1 m_Z}{\mu_-} \tan \theta_w - \sqrt{2} \frac{2}{3} \epsilon_1, \\ A_{\tilde{d}_L} &= -\frac{N_1 m_Z}{\mu_-} \left(\cot \theta_w + \frac{1}{3} \tan \theta_w \right) + \sqrt{2} \frac{2}{3} \epsilon_1, \\ A_{\tilde{d}_R} &= \frac{2}{3} \frac{N_1 m_Z}{\mu_-} \tan \theta_w + \sqrt{2} \frac{1}{3} \epsilon_1, \end{aligned} \quad (1d)$$

with N_1 and μ_- as defined in Ref. 11) and f_+ and ϵ_- as in Ref. 5). The terms involving ϵ_1 are due to additional mixing that arises due to non-zero tree-level gaugino masses.

The rates (1a-c) may be compared with

$$\Gamma(\tilde{q}_{L,R} \rightarrow q + \tilde{\gamma}) = \frac{B_{\tilde{q}_{L,R}}^2}{4} \alpha m_{\tilde{q}} \left(1 - \frac{m_{\tilde{\gamma}}^2}{m_{\tilde{q}}^2}\right)^2, \quad (1e)$$

with

$$\begin{aligned}
 B_{\tilde{u}_L} &= \sqrt{2} \frac{2}{3} + \frac{N_1 M_2}{\mu_-} (\cot \theta_w - \frac{1}{3} \tan \theta_w) E_1, \\
 B_{\tilde{u}_R} &= \sqrt{2} \frac{2}{3} - \frac{4}{3} \frac{N_1 M_2}{\mu_-} \tan \theta_w E_1, \\
 B_{\tilde{d}_L} &= -\sqrt{2} \frac{1}{3} - \frac{N_1 M_2}{\mu_-} (\cot \theta_w + \frac{1}{3} \tan \theta_w) E_1, \\
 B_{\tilde{d}_R} &= -\sqrt{2} \frac{1}{3} + \frac{2}{3} \frac{N_1 M_2}{\mu_-} \tan \theta_w E_1.
 \end{aligned} \tag{1f}$$

The branching ratios obtained from Eqs. (1a-f) are shown in Fig. 2a as functions of $m_{\tilde{W}}$ for a squark of mass $m_{\tilde{q}} = 60$ GeV.

If (a) $m_{\tilde{\chi}} < m_{\tilde{W}}$, then the decays $\tilde{W} \rightarrow \tilde{\ell} \nu$ or $\tilde{\ell} \tilde{\nu}$ and $Z \rightarrow \tilde{\ell} \tilde{\ell}$ or $\tilde{\nu} \tilde{\nu}$ dominate, in which case the non-observation of $Z^0 \rightarrow \tilde{W} \tilde{W} \rightarrow \ell^+ \ell^- + \cancel{p}_T$ events tells us⁵⁾ that

$$m_{\tilde{W}^\pm} \gtrsim 40 \text{ GeV}. \tag{2a}$$

This is shown by the line marked "Z" in Fig. 1. If (b) $m_{\tilde{\chi}} > m_{\tilde{W}}$ then the previous analysis of $Z^0 \rightarrow \tilde{W} \tilde{W}$ decays is modified, since now copious $\tilde{W} \rightarrow q \tilde{q} \tilde{\gamma}$ decays reduce the expected cross-section for $\ell^+ \ell^- + \cancel{p}_T$ events. However, the unsuccessful search⁸⁾ for $e^+ e^- \rightarrow \tilde{Z}^0 \tilde{\gamma}$ mediated by $\tilde{e}^\pm$ exchange tells us that if $m_{\tilde{\chi}} \lesssim 40$ GeV

$$m_{\tilde{Z}} \gtrsim 32 \text{ GeV}. \tag{2b}$$

this is indicated by the line labelled $\tilde{Z}$. Finally, the absence of winos in $e^+ e^-$ collisions implies $m_{\tilde{W}} \gtrsim 20$ GeV and is denoted by the line labelled $\tilde{W}$. To extend the validity of the previous monojet analyses we must consider anew the two cases (Aa) and (Ab).

Turning to Fig. 1b where $m_{\tilde{q}} > m_{\tilde{g}}$, if $m_{\tilde{W}} > m_{\tilde{g}}$ then the previous monojet analysis goes through unchanged. If (B) $m_{\tilde{W}} < m_{\tilde{g}}$, then $\tilde{g} \rightarrow q \tilde{q} \tilde{W}$ and possibly $\tilde{g} \rightarrow q \tilde{q} \tilde{Z}$ decays occur at the rates

$$\Gamma(\tilde{g} \rightarrow u \bar{d} \tilde{W}^-) = \frac{\alpha_s \alpha}{192 \pi} \frac{m_{\tilde{g}}^5}{m_{\tilde{q}_L}^4} \frac{f_+^2}{\sin^2 \theta_w} f(y_{\tilde{W}}), \tag{3a}$$

$$\Gamma(\tilde{g} \rightarrow q \bar{q} \tilde{Z}) = \frac{\alpha_s \alpha}{192\pi} m_{\tilde{g}}^5 \left(\frac{A_L^2}{m_{\tilde{q}_L}^4} + \frac{A_R^2}{m_{\tilde{q}_R}^4} \right) f(y_{\tilde{Z}}), \quad (3b)$$

with $y_{\tilde{W}, \tilde{Z}} = m_{\tilde{W}, \tilde{Z}}/m_{\tilde{g}}$ and

$$f(y) = (1-y^2)(y^6 + 2y^5 - 7y^4 + 20y^3 - 7y^2 + 2y + 1) + 24y^3(1-y+y^2) \times \ln y$$

should be compared with¹²⁾

$$\Gamma(\tilde{g} \rightarrow q \bar{q} \tilde{\gamma}) = \frac{\alpha_s \alpha}{192\pi} m_{\tilde{g}}^5 \left(\frac{B_L^2}{m_{\tilde{q}_L}^4} + \frac{B_R^2}{m_{\tilde{q}_R}^4} \right) f(y_{\tilde{\gamma}}), \quad (3c)$$

where $y_{\tilde{\gamma}} = m_{\tilde{\gamma}}/m_{\tilde{g}}$. The branching ratios obtained from Eqs. (3a-c) are shown in Fig. 2b.

For simplicity, we have assumed $m_{\tilde{q}} \gg m_{\tilde{g}}$. If (a) $m_{\tilde{q}} < m_{\tilde{W}}$ then we have the lower bound (2a) on $m_{\tilde{W}^\pm}$, while if (b) $m_{\tilde{q}} > m_{\tilde{W}}$ we still have the bound (2b) on $m_{\tilde{Z}^0}$. To extend the validity of the previous $\tilde{g}$ monojet analyses we must consider the two cases (Ba) and (Bb).

We note that in minimal $N = 1$ supergravity models with soft SUSY breaking terms induced by the super Higgs mechanism¹³⁾, the masses of the squarks and sleptons are related by¹⁴⁾

$$m_{\tilde{e}}^2 \simeq m_{\tilde{q}}^2 - 0.8 m_{\tilde{g}}^2.$$

In this case, the region where $m_{\tilde{W}} < m_{\tilde{q}}$ is much smaller than that shown in Fig. 1a and the region Ab is very small. Moreover, depending on the gluino mass, the line marked Z may be well above the $m_{\tilde{W}} = m_{\tilde{q}}$ line. The sizes of the regions Ba and Bb in Fig. 1b are, however, representative of the situation in this class of models for $m_{\tilde{q}} \simeq 70$ GeV.

We start by considering the most straightforward case (Aa) where $m_{\tilde{q}} < m_{\tilde{W}} < m_{\tilde{g}}$ and so the bound (2a) applies. In addition to the $\tilde{q} \rightarrow q \tilde{\gamma}$ decay, the $\tilde{q}_L \rightarrow q \tilde{W}$ decay is (and $\tilde{q} \rightarrow q \tilde{Z}$ may be) kinematically accessible. The wino (zino) decays exclusively into a lepton-slepton pair. The slepton then decays into a lepton and a photino. We have assumed that a muon with transverse momentum greater

than $p_{T\mu}^0$ and pseudorapidity less than $|\eta_\mu^0|$ will always be recognized as such. For electrons, in addition to the acceptance cuts on p_T and $|\eta|$, we require an isolation cut since hard electrons inside a jet cannot be distinguished from hadrons. For electrons we therefore require in addition that $|\vec{p}_{Te}| \geq 4 |\vec{p}_{T\text{parton}}|$ for any parton within $\Delta r = 1$ of the electron. If the electron is not isolated, we have included it as part of the jet. Thus, in principle, we can obtain n lepton + m jet signature where $0 \leq n \leq 4$. Of course, not all the leptons will pass our cuts.

Motivated by the fact (see Fig. 2a) that the squark branching fraction into zinos averaged over the handedness and flavours of squarks (with equal weights) is less than 16% - compare this with 51% (33%) for the decay into the photino (wino) for the same value of $m_{\tilde{W}}/m_{\tilde{q}}$ - and falls off faster than the branching into winos, we have neglected events from $\tilde{q} \rightarrow q\tilde{Z}$ decays. Since we treat the branching fractions of the squarks correctly, we are slightly underestimating the normalizations for the various cross-sections. (Since the $\tilde{Z} \rightarrow \tilde{\nu}\nu$ with a branching fraction of 2/3, the cross-section into the jet + lepton mode is even further suppressed). As a further simplification, we have ignored events from $\tilde{q} \rightarrow q\tilde{W}$, $\tilde{W} \rightarrow \tau\tilde{\nu}$ or $\tilde{\nu}\nu$ decays. The contribution to n lepton + m jet signatures with $n \geq 1$ is suppressed by the branching ratio for $\tau \rightarrow$ leptons. Moreover, the momenta of the τ decay products resulting from the cascade are substantially degraded and only a small fraction of the jets (or leptons) from this decay will pass our cuts. Again, ignoring these events only causes a modest underestimate of the cross-section.

In our calculations on the m jet + n lepton cross-sections, we have used the structure functions of Ref. 15), Set 1, with $\Lambda = 0.2$. We have incorporated the UA1 inspired cuts with

$$\begin{aligned} p_{Te}^0 &= 15 \text{ GeV} , & p_{T\mu}^0 &= 3 \text{ GeV} ; \\ |\eta_e^0| &= 3.0 , & |\eta_\mu^0| &= 2.0 ; \\ |p_{Tj1}| &\geq 25 \text{ GeV} , & |p_{Tj2}| &\geq 12 \text{ GeV} \text{ and } |\eta_{jet}| \leq 2.5. \end{aligned}$$

We have also coalesced partons within $\Delta r \equiv (\Delta\eta^2 + \Delta\phi^2)^{\frac{1}{2}} < 1$. Finally, we have required $p_T > 4\sigma$ where $\sigma = 0.7 \sqrt{\Sigma E_T + 20 \text{ GeV}}$ and 20 GeV is the E_T from a typical minimum bias event. We have also incorporated a centre-of-mass parton smearing and experimental resolutions as in Baer et al.⁴⁾. The relevant formulae for squark production - separating out $\tilde{q}_L\tilde{q}_L$, $\tilde{q}_L\tilde{q}_R$ and $\tilde{q}_R\tilde{q}_R$ production - may be found

in Ref. 6); formulae for squark-gluino or gluino pair production may be found in Ref. 17). The results of our computation for the monojet and dijet cross-sections from $\tilde{q}\tilde{q}$ (which includes $\tilde{q}\tilde{q}$) production (with $m_{\tilde{q}} < m_{\tilde{g}}$) are shown in Fig. 3a for $m_{\tilde{q}} < m_{\tilde{W}}$ (case Aa), and Fig. 3b for $m_{\tilde{q}} = m_{\tilde{W}} > m_{\tilde{g}}$ (case Ab). For convenience, we have plotted the reduction factor,

$$R \equiv \frac{\sigma(p\bar{p} \rightarrow \text{jets} + \cancel{p}_T; \tilde{q} \rightarrow \tilde{\gamma}, \tilde{W} \text{ or } \tilde{Z})}{\sigma(p\bar{p} \rightarrow \text{jets} + \cancel{p}_T; \tilde{q} \rightarrow \tilde{\gamma})} \quad (4)$$

The approximations we have made (neglecting $\tilde{q} \rightarrow \tilde{Z}$ and $\tilde{W} \rightarrow \tau$ or $\tilde{\tau}$) make the value plotted a lower bound on the true reduction factor. Two sets of curves are given in Fig. 3a: reduction factors with $m_{\tilde{g}} = \infty$ and $m_{\tilde{g}} = m_{\tilde{q}} + 5$ GeV. In the $m_{\tilde{g}} = \infty$ case, only $\tilde{q}_L\tilde{q}_L$ and $\tilde{q}_R\tilde{q}_R$ pairs are being produced, and in equal quantities. The right-handed squarks suffer little reduction in ability to produce mono and dijets - only that due to the small branching fraction from $\tilde{q} \rightarrow q\tilde{Z}$ decays. Producing jets + $\cancel{p}_T$ from left-handed squark pairs will be more difficult: in this case the branching fraction to quark plus photino is small. Furthermore the jet coming from the decay $\tilde{q} \rightarrow q\tilde{W}$ will be less energetic than typical jets from $\tilde{q} \rightarrow q\tilde{\gamma}$, and less likely to pass the selection criteria. In the case where $m_{\tilde{g}} = m_{\tilde{q}} + 5$ GeV, production of $\tilde{q}_R\tilde{q}_L$ pairs becomes comparable to production of $\tilde{q}_L\tilde{q}_L$ and $\tilde{q}_R\tilde{q}_R$, hence we have a greater proportion of events containing $\tilde{q} \rightarrow q\tilde{W}$ decays. The overall efficiency to produce jets of high energy is decreased, and the reduction factor is smaller than the $m_{\tilde{g}} = \infty$ case. The reduction factor could be as small as 0.45 for $m_{\tilde{q}} = 80$ GeV - though we would actually expect it to be larger, since our plot is a lower bound, and we take $m_{\tilde{W}} = 40$ GeV to give the maximum possible reduction.

Figure 3b illustrates the reduction factor for the region Ab in Fig. 1: $m_{\tilde{q}} \approx m_{\tilde{W}} > m_{\tilde{g}}$. The wino now decays to three bodies via virtual squarks and sleptons, via the following reactions:

$$\begin{aligned} \tilde{W}^- &\rightarrow e^- \bar{\nu} \tilde{\gamma}, \\ &\mu^- \bar{\nu} \tilde{\gamma} \\ &\tau^- \bar{\nu} \tilde{\gamma} \\ &d \bar{u} \tilde{\gamma} \\ &s \bar{c} \tilde{\gamma} \end{aligned} \quad (5)$$

For this calculation, we take $BF(\tilde{W} \rightarrow e\tilde{\nu}) = 1/9^{*)}$, and approximate the decay matrix element by a constant. We expect this to be a reasonable approximation since the results are dominantly governed by the event selection criteria rather than the details of the matrix element. Since now a greater percentage of the squark decay debris is going into hadrons, we find the reduction factor to be in general larger than those presented in Fig. 3a.

If $m_{\tilde{g}} > m_{\tilde{q}}$, but nearby in mass, then one must also consider $\tilde{g}\tilde{q}$ and $\tilde{g}\tilde{g}$ production, where $g \rightarrow \tilde{q}\tilde{q}$. Squarks from these sources will be produced in the ratio $\tilde{q}_R\tilde{q}_R:\tilde{q}_L\tilde{q}_L:\tilde{q}_R\tilde{q}_L = 1:1:2$ in the limit $m_{\tilde{q}_L} = m_{\tilde{q}_R}$. Numerically, this is comparable to the same ratio from $\tilde{q}\tilde{q}$ production when $m_{\tilde{g}} = m_{\tilde{q}} + 5$ GeV. But since the gluino decay gives rise to a greater proportion of hadrons in the final state, one expects the reduction factor to be larger than that obtained from $\tilde{q}\tilde{q}$ production, where $m_{\tilde{g}} = m_{\tilde{q}} + 5$ GeV.

We now consider the regions illustrated in Fig. 1b, where $m_{\tilde{g}} < m_{\tilde{q}}$. In this case, $\tilde{g} \rightarrow \tilde{q}\tilde{q}\tilde{\gamma}$, $\tilde{q}\tilde{q}\tilde{W}$ or $\tilde{q}\tilde{q}\tilde{Z}$. Branching fractions for these decays are given in Fig. 2b for $m_{\tilde{g}} = 60$ GeV, for variable wino mass. We note these branching fractions into winos and zinos are always smaller than the corresponding squark branching fractions, for similar mass choices. These small branching fractions, along with a relatively greater proportion of hadrons in the final state (compared to the squark case) will result in reduction factors always greater than those obtained in the corresponding squark case.

A reduction in the monojet and dijet cross-sections is not the only effect of squark decays to gauginos. There can also be present at some level n jet + ($m > 1$) lepton + $\cancel{p}_T$ signals, which can reach observable levels. In Fig. 4 we illustrate the largest n jet + m lepton + $\cancel{p}_T$ signals from $\tilde{q}\tilde{q}$ production, for $m_{\tilde{q}} = 60$ GeV, $m_{\tilde{g}} = 65$ GeV, $m_{\tilde{\chi}} = 30$ GeV and $m_{\tilde{\gamma}} = 5.9$ GeV. We implement the previously mentioned cuts appropriate to the UA1 detector. We find a substantial signal for events with a single muon + 0-2 jets + $\cancel{p}_T > \max(15 \text{ GeV}, 4\sigma)$, which can be as high as 27 pb for $m_{\tilde{W}} = 43$ GeV. In our figure, the lower scale of the plot is expanded to better illustrate the leptonic signals. Multilepton events will also be present, but at rates of less than a picobarn. We emphasize again that

*) This is a lower limit on the branching ratio which varies between 1/7 and 1/9 over a range of sparticle masses¹⁸⁾ and is close to 1/9 unless $m_{\tilde{\chi}}$ approaches the wino mass.

these cross-sections are lower bounds, since we have included neither $\tilde{q} \rightarrow q\tilde{Z}$ decays nor $\tilde{q} \rightarrow q\tilde{W}$, $\tilde{W} \rightarrow \tilde{\tau}\nu + \tau\tilde{\nu}$ decays.

We conclude that in addition an unimportant reduction in the 1, 2 jets + 0 lepton + $\cancel{p}_T$ signals, gaugino decays of squarks may also have observable 0, 1, 2 jet + 1 lepton + $\cancel{p}_T$ signals. Such signals could be of great potential interest if winos are too heavy to be pair produced by gauge boson decays since then the $\tilde{q} \rightarrow q\tilde{W}$ decays could lead to the cleanest signatures for winos at least at hadron colliders.

REFERENCES

- 1) J. Ellis and H. Kowalski - Phys.Lett. 142B (1984) 441; Nucl.Phys. B246 (1984) 189; CERN Preprints TH. 4072 (1985), TH. 4126 (1985);
V. Barger, K. Hagiwara and W.-Y. Keung - Phys.Lett. 145B (1984) 147;
A.R. Allan, E. Glover and A.D. Martin - Phys.Lett. 146B (1984) 247.
- 2) E. Reya and D.P. Roy - Phys.Lett. 141B (1984) 442; Phys.Rev.Lett. 53 (1984) 881;
M. Glück, E. Reya and D.P. Roy - Phys.Lett. 155B (1985) 284;
V. Barger, K. Hagiwara, W.-Y. Keung and J. Woodside - Phys.Rev. D31 (1985) 528.
- 3) M.J. Herrero, L.E. Ibáñez, C. López and F.J. Yndurain - Phys.Lett. 132B (1983) 199; *ibid.* 145B (1984) 430;
V. Barger, K. Hagiwara, W.-Y. Keung and J. Woodside - Phys.Rev.Lett. 53 (1984) 641; Univ. of Wisconsin Preprint MAD/PH/232 (1985);
A. De Rújula and R. Petronzio - CERN Preprint TH. 4070 (1984);
R.M. Barnett, H.E. Haber and G.L. Kane - Phys.Rev.Lett. 54 (1985) 1983.
- 4) R. Barbieri, N. Cabibbo, L. Maiani and S. Petrarca - Phys.Lett. 127B (1983) 458;
N. Cabibbo, L. Maiani and S. Petrarca - Phys.Lett. 132B (1983) 195;
R.M. Barnett, K. Lackner and H. Haber - Phys.Rev.Lett. 51 (1983) 176;
R. Barnett, H. Haber and K. Lackner - Phys.Rev. D29 (1984) 1381.
H. Baer, J. Ellis, D.V. Nanopoulos and X. Tata - Phys. Lett. 153B (1985) 265.
- 5) H. Baer and X. Tata - Phys.Lett. 155B (1985) 278.
- 6) UAl Collaboration, G. Arnison et al. - Phys.Lett. 139B (1984) 115.
- 7) D.A. Dicus, S. Nandi, W. Repko and X. Tata - Phys.Rev. D29 (1984) 67;
S. Gottlieb and T. Wyler - Univ. of California at San Diego Preprint UCSD 10P10-244 (1985).
- 8) B. Adeva et al. - Phys.Lett. 53 (1984) 1806;
JADE Collaboration, W. Bartel et al. - Phys.Lett. 146B (1984) 126;
Mark J Collaboration, B. Adeva et al. - Phys.Lett. 152B (1985) 439.
- 9) D.A. Dicus, S. Nandi, W. Repko and X. Tata - Phys.Rev. D29 (1984) 1317;
ibid. 30 (1984) 1112;
M. Glück and E. Reya - Phys.Rev. D31 (1985) 620.
- 10) M. Glück and E. Reya - Phys.Rev.Lett. 51 (1983) 867;
V. Barger, W.-Y. Keung and R. Phillips - Univ. of Wisconsin Preprints MAD/PH/219, 223 (1984), MAD/PH/228 (1985).
- 11) D.A. Dicus, S. Nandi and X. Tata - Phys.Lett. 129B (1983) 451.
- 12) H.E. Haber and G.L. Kane - Nucl.Phys. B232 (1984) 333.
- 13) For recent reviews of supergravity models, see:
H.P. Nilles - Physics Reports 110C (1984) 1;
J. Ellis - CERN Preprint TH. 3802 (1984);
D.V. Nanopoulos - CERN Preprint TH. 3995 (1984).

- 14) C. Kounnas, A.B. Lahanas, D.V. Nanopoulos and M. Quirós - Phys.Lett. 132B (1983) 95; Nucl.Phys. B236 (1984) 438.
See also:
J. Ellis and M. Sher - Phys.Lett. 148B (1984) 309;
L. Ibáñez, C. López and C. Muñoz - CERN Preprint TH. 4071 (1984);
K. Enqvist, D.V. Nanopoulos and A.B. Lahanas - Phys.Lett. 155B (1985) 83;
L.J. Hall and J. Polchinski - Phys.Lett. 152B (1985) 335.
- 15) D.W. Duke and J.F. Owens - Phys.Rev. D30 (1984) 49.
- 16) S. Dawson, E. Eichten and C. Quigg - Phys. Rev. D31 (1985) 1581;
H. Baer and X. Tata - CERN Preprint TH. 4158 (1985); Phys.Lett. B (in press).
- 17) P.R. Harrison and C.H. Llewellyn Smith - Nucl.Phys. B213 (1983) 223;
Erratum B223 (1983) 542.
- 18) T. Schimert, C. Burgess and X. Tata - Phys.Rev. D (in press).

FIGURE CAPTIONS

Figure 1 Regions of parameter space a) $m_{\tilde{q}}^{\sim}$ vs. $m_{\tilde{W}}^{\sim}$ in units of $m_{\tilde{g}}^{\sim}$, assumed to be $>m_{\tilde{q}}^{\sim}$, and b) $m_{\tilde{W}}^{\sim}$ vs. $m_{\tilde{g}}^{\sim}$ in units of $m_{\tilde{q}}^{\sim}$, assumed to be $>m_{\tilde{g}}^{\sim}$. In Fig. 1a, region Aa is where $m_{\tilde{g}}^{\sim} > m_{\tilde{q}}^{\sim} > m_{\tilde{W}}^{\sim} > m_{\tilde{\chi}}^{\sim}$, and region Ab is where $m_{\tilde{g}}^{\sim} > m_{\tilde{q}}^{\sim}$, $m_{\tilde{\chi}}^{\sim} > m_{\tilde{W}}^{\sim}$. Figure 1b contains the regions Ba, where $m_{\tilde{q}}^{\sim} > m_{\tilde{g}}^{\sim} > m_{\tilde{W}}^{\sim} > m_{\tilde{\chi}}^{\sim}$, and region Bb is where $m_{\tilde{\chi}}^{\sim}, m_{\tilde{q}}^{\sim} > m_{\tilde{g}}^{\sim} > m_{\tilde{W}}^{\sim}$. The line (UA1) denotes previous limits on squark and gluino masses, and the lines $Z, \tilde{W}$ and $\tilde{Z}$ denote limits on the wino and zino masses. The double-headed arrows indicate that the position of the dashed lines (which indicate the various bounds) may move around, while the thick arrows indicate the position of the allowed regions. Also shown schematically are the lines where $m_{\tilde{W}}^{\sim} = m_{\tilde{q}}^{\sim}$ or $m_{\tilde{g}}^{\sim}$, and where $m_{\tilde{W}}^{\sim} = m_{\tilde{\chi}}^{\sim}$, if one uses minimal $N = 1$ supergravity mass relations.

Figure 2 Branching fractions for decays into zinos, winos and photinos versus wino mass for a) left- and right-handed up- and down-type squarks, and b) gluinos. In a) and in b), the squark and gluino mass is taken to be 60 GeV, while the photino mass is 5.9 GeV.

Figure 3 Theoretical lower bounds on the reduction factor R , where $R = \sigma(p\bar{p} \rightarrow \text{monojets or dijets}; \tilde{q}\bar{\tilde{q}}, \tilde{W} \text{ or } \tilde{Z}) / \sigma(p\bar{p} \rightarrow \text{monojets or dijets}; \tilde{q}\bar{\tilde{q}})$. In case a) $m_{\tilde{\chi}}^{\sim} < m_{\tilde{W}}^{\sim} = 40$ GeV, and the curves correspond to $m_{\tilde{g}}^{\sim} = \infty$ and $m_{\tilde{g}}^{\sim} = m_{\tilde{q}}^{\sim} + 5$ GeV. Case b) has $m_{\tilde{\chi}}^{\sim} > m_{\tilde{W}}^{\sim} = 30$ GeV.

Figure 4 Relative rates for different topological signatures of $p\bar{p} \rightarrow \tilde{q}\bar{\tilde{q}}, \tilde{q}\tilde{q}$ versus $m_{\tilde{W}}^{\sim}$. The scale 0-13 GeV is enhanced to exhibit better the leptonic cross-sections. Other signatures of the form n jet + m lepton + p_T will be present, but at much smaller rates than the plotted signals. Scenario parameters are given in the Figure; we require $p_T > \max(15, 4\sigma)$ for all events, along with other cuts described in the text.

Fig. 1a

Fig. 1b

Fig. 2a

Fig. 2b

Fig. 3

Fig. 4