Events with Large Missing Transverse Energy at the CERN Collider
(Paper III): Mass Limits on Supersymmetric Particles

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ABSTRACT

A sample of events with large missing transverse energy from 715 nb^{-1} of data from the UA1 experiment at the CERN proton-antiproton collider is used to search for evidence of supersymmetric particle production. Assuming that the photino is the lightest supersymmetric particle and that it is massless, we find a limit on the squark mass of $m_{\tilde{q}} > 45 \text{ GeV}/c^2$ at 90% C.L., independently of the gluino mass. Similarly, we find a limit on the gluino mass of $m_{\tilde{g}} > 53 \text{ GeV}/c^2$ (at 90% C.L.) independently of the squark mass, provided that the gluino is not long-lived (i.e. provided that the squark is not too heavy, $m_{\tilde{q}} < \sim 1 \text{ TeV}/c^2$). For equal squark and gluino masses we find a limit $m_{\tilde{q}}=m_{\tilde{g}} > 75 \text{ GeV}/c^2$ at 90% C.L. The effect of a non-zero photino mass on these limits is studied.

1.-Introduction. In two previous papers[1], events containing one or more hadronic jets produced in association with large missing transverse energy in proton-antiproton collisions were used to test the standard model and to search for evidence of new generations of sequential leptons. Evidence was presented for the decay $W \rightarrow \tau \nu$, and the universality of e , μ and τ lepton couplings to the weak charged current was tested to a precision of 10%. Significant limits were placed on the mass m_L of a new sequential charged heavy lepton L ($m_L > 41 \text{ GeV}/c^2$ at 90% C.L.) and on the total number N_ν of light neutrino species ($N_\nu \leq 10$ at 90% C.L.).

In this letter, we study possible contributions to the large missing transverse energy event sample from supersymmetric particle (squark and gluino) production[2]. In most models, squarks and gluinos should be pair produced as $\bar{p}p \rightarrow \bar{q}\bar{q}, \bar{q}\bar{g}, \bar{g}\bar{g} + X$ with cross-sections which are calculable within perturbative QCD and which range (for $\sqrt{s}=630 \text{ GeV}$) from 0.1-100 nb for masses in the range 70-20 GeV/c^2 [3–5]. The squarks and gluinos then decay into final states containing the lightest supersymmetric particle, which we shall here take to be the photino. The photino is usually assumed to be stable and is expected to have a very small interaction cross section, of the same order as the neutrino cross section. It would therefore escape detection.

If the gluino mass is greater than the squark mass, the dominant production mechanism is $\bar{p}p \rightarrow \bar{q}\bar{q} + X$, and the squarks will decay through the channel $\bar{q} \rightarrow q\tilde{\gamma}$. The final state therefore contains two quarks and two photinos, giving the signature of large missing transverse energy (the vector sum of the two decay photinos) in association with two large transverse energy jets. Similarly, if the gluino mass is smaller than the squark mass, the dominant production mechanism is $\bar{p}p \rightarrow \bar{g}\bar{g} + X$, with gluino decay via $\bar{g} \rightarrow \bar{q}q\tilde{\gamma}$, and the final state would contain large missing transverse energy plus four quark jets. For large squark or gluino mass, the photinos and quarks from the squark or gluino decays will usually be produced at large angles with respect to the original squark or gluino direction. Supersymmetric events would therefore be expected to be more isotropic than events from conventional sources of missing transverse energy (e.g. $\bar{p}p \rightarrow \bar{b}b + X$, $b \rightarrow c\bar{e}\nu$), which tend to produce events with jets back-to-back in the transverse plane.

Direct searches for squarks in e^+e^- collisions have placed a lower mass limit of $21.5 \text{ GeV}/c^2$ at 90% confidence level[6]. Searches for gluinos have been made in Υ [7] and χ_b decays[8], in

beam dump experiments[9], in an emulsion experiment[10], and in stable particle searches[4,11]. The mass limits from these experiments are shown in figure 1. In this analysis, we shall consider squark masses greater than $20 \text{ GeV}/c^2$ and gluino masses greater than $4 \text{ GeV}/c^2$.

2.-Data. This analysis uses data taken with the UA1 detector in the period 1983-85 at proton- antiproton centre of mass energies of 546 GeV (118 nb^{-1}) and 630 GeV (597 nb^{-1}). Events were recorded using several hardware triggers on the transverse energy deposited in the calorimetry, including a trigger on the horizontal component of the transverse energy imbalance in the event[12]. Events with large missing transverse energy and two or more hadronic jets were selected according to the following criteria:

1) *missing transverse energy*, $E_T^{\text{miss}} > 15 \text{ GeV}$ and $N_\sigma > 4$, where N_σ is defined as $E_T^{\text{miss}} / (0.7 \sqrt{\Sigma E_T})$ [1] and transverse energies are measured in GeV . Here, E_T^{miss} is the magnitude of the missing transverse energy vector formed by summing the transverse energy vectors of all calorimeter cells. Similarly, ΣE_T is the total scalar sum of the transverse energy observed in the calorimetry. N_σ is a measure of the experimental significance of the observed missing transverse energy.

2) *two or more jets*[13] observed in the calorimeters with $E_T > 12 \text{ GeV}$ and $|\eta| < 2.5$.

3) *one or more tracks* observed in the drift chambers with $p_T > 1 \text{ GeV}/c$ within a cone of size $\Delta R = 0.4$ centred on the calorimeter jet axis ($\Delta R^2 \equiv \Delta\phi^2 + \Delta\eta^2$, where ϕ is the azimuthal angle and η is the pseudorapidity) for the highest E_T jet in the event.

4) *veto of events with an electron or muon candidate* in order to remove contributions from $W \rightarrow e\nu$ or $\mu\nu$ or heavy flavour semi-leptonic decays. For this purpose we have developed an algorithm for removing electrons or muons having tracks with $p_T > 10 \text{ GeV}/c$. In addition, events were scanned and removed if they had muon candidates with $p_T > 3 \text{ GeV}/c$. The cuts used to define electrons and muons for veto purposes in this analysis are less stringent than those used to select low background samples of W events[14].

5) *veto of $W \rightarrow \tau\nu$, $\tau \rightarrow \text{hadrons} + \nu$ candidates* by requiring that the relative τ log-likelihood L_τ [1] satisfy $L_\tau < 0$. L_τ is computed from the relative probabilities for the highest E_T jet in each event

to fit the predicted τ properties based on (1) the angular size of the jet, (2) the angular matching of the leading charged particle with the calorimeter jet axis, and (3) the charged particle multiplicity associated to the jet.

6) *veto of back-to-back jet topology*, by requiring that the difference $\Delta\phi$ in azimuthal angle between the two highest transverse energy jets satisfy $\Delta\phi < 140^\circ$.

Additional technical cuts were applied to remove background events such as cosmic rays, beam halo and double interactions. The events remaining after these cuts were scanned on an interactive graphics facility to check that the observed missing energy was not due to residual background of this type or to problems in the detector reconstruction: no such cases were found. A total of 4 events passed all the above selection criteria. Of these events, three contain exactly two jets (with jet $E_T > 12$ GeV) and one contains three jets.

The histogram in figure 2 shows the $\Delta\phi$ distribution for the large missing E_T multijet sample before applying the cut $\Delta\phi < 140^\circ$ (23 events). This distribution is strongly peaked towards $\Delta\phi = 180^\circ$, i.e. the two highest E_T jets in the event are usually produced back-to-back in azimuth. Such topologies are expected from heavy flavour production and from jet fluctuation background (i.e. events with no genuine missing energy but with apparent missing transverse energy arising from fluctuations in the calorimeter response to jets). In ref. [1], in place of the requirement $\Delta\phi < 140^\circ$, rather tight requirements were made on the missing transverse energy isolation and on back-to-back jet topologies to remove heavy flavour and jet fluctuation background[15]. There, 24 events were selected with $L_T < 0$, two of which were multijet events. Both of these multijet events are contained in the $\Delta\phi < 140^\circ$ multijet sample of 4 events used in this paper. (One of these events has also been discussed in detail elsewhere [16] in connection with studies of high transverse momentum W and Z^0 production.) For squark production, the $\Delta\phi < 140^\circ$ multijet selection and the multijet selection of reference [1] have essentially the same acceptance. For gluino production however, where the jet multiplicity tends to be higher, the $\Delta\phi < 140^\circ$ selection has significantly better acceptance (typically 50-100% higher), especially at lower gluino mass.

3.-Origin of multijet events. We now consider the expected contribution to the

$\Delta\phi < 140^\circ$ multijet sample from conventional (standard model) processes and from jet fluctuation background. Known sources of large transverse momentum prompt neutrinos which must be considered are W decays ($W \rightarrow e\nu, \mu\nu, \tau\nu, cs$), Z^0 decays ($Z^0 \rightarrow \bar{\nu}\nu, \bar{c}c, \bar{b}b$) and semi-leptonic decays of heavy quarks (e.g. $\bar{p}p \rightarrow \bar{b}b + X, b \rightarrow c e \nu$). The expected contributions from these processes to the multijet event sample were evaluated using the ISAJET Monte Carlo program[17], together with a full simulation of the UA1 detector including the hardware triggers. The ISAJET Monte Carlo generates a complete proton-antiproton event, including the effects of spectator particles. The spectator particle parameters in ISAJET were adjusted to give jet profiles consistent with UA1 data. Similarly, the transverse momentum distributions for the W and Z^0 bosons were adjusted to agree with those measured by UA1[16]. The number of events generated for each physics process corresponds to approximately 10 times our integrated luminosity. The background due to fluctuations of detector response has been evaluated with a separate Monte Carlo technique which uses UA1 jet data and is described in ref. [1].

The $\Delta\phi$ distribution computed from the Monte Carlo (before applying the $\Delta\phi < 140^\circ$ cut) is shown as the dashed curve in figure 2. The curve has been normalised to the data sample of 23 events. The total predicted contribution from standard model processes and from jet fluctuation background is $43.4 \pm 3.7 \pm 12.0$, in reasonable agreement with the number of events observed. The systematic error of ± 12.0 events is due largely to uncertainties in heavy flavour cross sections and the normalisation of the jet fluctuation background. The peak at $\Delta\phi = 180^\circ$ is dominated by heavy flavour production (9.2 events) and by jet fluctuation background (29.8 events). The contribution from W and Z^0 decays (4.4 events) gives an essentially flat $\Delta\phi$ distribution.

The total predicted contribution to the $N_\phi > 4, \Delta\phi < 140^\circ$ sample from standard model processes and from jet fluctuation background is 5.2 events, compared to 4 events observed. The dominant contributions are from $Z \rightarrow \bar{\nu}\nu$ decays (1.2 events), $W \rightarrow \tau\nu$ decays (1.9 events) and heavy quark production (2.0 events). The predicted background from jet fluctuations is small (0.2 events). The statistical error on the Monte Carlo prediction of 5.2 events is ± 1.9 events. This error includes the statistical errors on the measurement of the high transverse momentum W and Z^0 cross sections (1.5 events) and the statistical errors of the Monte Carlo generation (1.2 events). The total

systematic error is ± 1.0 events and contains the uncertainties in the jet energy scale (0.4 events), in the jet fluctuation background (0.1 events), in the τ acceptance (0.2 events), and in the heavy flavour cross sections (0.9 events).

In addition, we have calculated the expected contribution to the $\Delta\phi < 140^\circ$ multijet sample from the top quark due to the processes $W \rightarrow t \bar{b}$, $Z^0 \rightarrow \bar{t} t$, and strong $\bar{t} t$ production. For a top quark mass of $25 \text{ GeV}/c^2$ we expect an additional 2.1 ± 0.4 events, falling to 0.7 ± 0.3 events for a mass of $50 \text{ GeV}/c^2$.

In summary, we find good agreement between the 4 events observed and the standard model expectation of $5.2 \pm 1.9 \pm 1.0$ events. Within the limited statistics, the topology of the events observed (and in particular the missing transverse energy and jet transverse energy distributions) is also in agreement with expectation. Given this agreement, we now consider the event rates to be expected from supersymmetric particle production and determine the limits that can be set on the allowed range of squark and gluino masses. In the following analysis, top quark contributions were not included in the background. Inclusion of such contributions would increase the squark and gluino mass limits derived below.

4.-The Supersymmetry Model. We assume that the photino is the lightest supersymmetric particle, and initially take it to be massless (the effect on our results of a non-zero photino mass will be discussed below). We assume that the u,d,s,c and b squarks are mass degenerate, and that the left- and right-handed squarks (i.e. the partners of the left- and right-handed quarks) have equal mass (the t-squark is ignored). We do not consider processes involving the supersymmetric partners of the W,Z and Higgs bosons or of the known leptons. The model thus contains two free parameters, the squark and gluino masses $m_{\tilde{q}}$ and $m_{\tilde{g}}$.

The decay modes and branching fractions for the squarks and gluinos are taken from ref [3]. If $m_{\tilde{g}} > m_{\tilde{q}}$, the only allowed decays are $\tilde{g} \rightarrow \bar{q}q$ and $\tilde{q} \rightarrow q\tilde{g}$. If $m_{\tilde{q}} > m_{\tilde{g}}$, the gluino decays 100% of the time as $\tilde{g} \rightarrow \bar{q}q\tilde{\gamma}$, while the allowed squark decays are $\tilde{q} \rightarrow q\tilde{g}$ with branching fraction $r/(r+1)$ and $\tilde{q} \rightarrow q\tilde{\gamma}$ with branching fraction $1/(r+1)$, where $r = (\alpha_s / \alpha e_q^2) \cdot (1 - m_{\tilde{g}}^2/m_{\tilde{q}}^2)^2$ and e_q is the quark charge [18]. Thus gluino decays always give rise to the final state $\bar{q}q\tilde{\gamma}$, while squark decays

produce the dominant final states $q\bar{\gamma}$ (if $m_{\tilde{g}} > m_{\tilde{q}}$) or $\bar{q}q\bar{\gamma}$ (if $m_{\tilde{q}} > m_{\tilde{g}}$). For $m_{\tilde{g}} > m_{\tilde{q}}$, the dominant production mechanism is $\bar{p}p \rightarrow \tilde{q}\bar{\tilde{q}} + X$, and the final state contains two photinos and two quark jets. For $m_{\tilde{q}} > m_{\tilde{g}}$, the dominant production mechanism is $\bar{p}p \rightarrow \tilde{g}\tilde{g} + X$ and the final state contains two photinos and four quark jets.

The expected contributions to the multijet sample from squark and gluino production were again evaluated using the ISAJET Monte Carlo program, with full simulation of the UA1 detector. Events were generated for a wide range of squark and gluino masses, and were passed through the same selection programs as were used for the data. The matrix elements for supersymmetric particle production are given in ref [4]. All hard scattering processes of order α_s^2 ($\bar{p}p \rightarrow \tilde{g}\tilde{g}, \tilde{g}\tilde{q}$ and $\tilde{q}\bar{\tilde{q}}$) and of order $\alpha\alpha_s$ ($\bar{p}p \rightarrow \tilde{q}\bar{\gamma}, \tilde{g}\bar{\gamma}$) were included in the calculation. The proton structure functions were calculated using the parameterisation of Eichten et al.[19] with $\Lambda=200$ MeV. Gluon bremsstrahlung from initial and final state partons (including squarks and gluinos) is included in the ISAJET program. Squark and gluino decays were computed according to 2-body or 3-body phase space, and the quarks from these decays were then fragmented according to an independent fragmentation model [17].

As discussed in the introduction, high mass squark or gluino production would be expected to give rise in general to rather isotropic events, unlike the coplanar events expected from heavy flavour production and from jet fluctuation background. The $\Delta\phi$ distribution for a squark mass of $60 \text{ GeV}/c^2$ and a gluino mass of $70 \text{ GeV}/c^2$ for example (the dot-dash curve in figure 2) is essentially flat. As the squark or gluino mass decreases however, the events become more coplanar and we expect the acceptance to decrease. Further, the missing transverse energy spectrum becomes softer as the squark or gluino mass decreases, partly because the decay photinos have smaller p_T and partly because the two photinos tend to be produced back-to-back in azimuth, the missing transverse energies from the two photinos thus tending to cancel each other.

As will be shown below, the expected event rate from "direct" gluino production ($\bar{p}p \rightarrow \tilde{g}\tilde{g}$) alone is insufficient to exclude gluinos with masses $< 20 \text{ GeV}/c^2$. For light gluinos therefore, we have also evaluated the contribution from "indirect" gluino pair production in gluon fragmentation, i.e. $\bar{p}p \rightarrow gX, g \rightarrow \tilde{g}\tilde{g}$. For "indirect" gluino production, the two decay photinos will tend to be

produced in the same hemisphere, thus enhancing the observed missing transverse energy. The gluon fragmentation process $g \rightarrow \tilde{g}\tilde{g}$ was implemented in ISAJET using the Altarelli-Parisi evolution function given in ref [20].

Finally, we note that, since gluino decay can only proceed via the exchange of a virtual squark, the gluino becomes long-lived ($\tau_{\tilde{g}} > 10^{-10}$ secs) when the squark mass becomes large ($m_{\tilde{q}} > 2$ TeV/c²). For a massless photino, the gluino lifetime is $\tau(\tilde{g} \rightarrow \bar{q}q\tilde{\gamma}) \approx 4 \times 10^{-8} \text{sec} (m_{\tilde{q}}^4/m_{\tilde{g}}^5)$ [4], with $m_{\tilde{q}}$ in TeV/c² and $m_{\tilde{g}}$ in GeV/c² (see figure 1). The finite gluino lifetime was not implemented in the Monte Carlo; we comment on this below.

5.-Results. The main characteristics expected from supersymmetric particle production are most easily seen by considering the two limiting cases (a) where the squark mass becomes very large so that $\tilde{g}\tilde{g}$ production dominates and (b) where the gluino mass becomes large so that $\bar{q}\tilde{q}$ production dominates.

Figure 3(a) shows the predicted event rate for the $\Delta\phi < 140^\circ$ multijet selection as a function of gluino mass for infinitely large squark mass ($m_{\tilde{q}} \rightarrow \infty$). For large gluino mass, the rate is dominated by "direct" gluino pair production ($\bar{p}p \rightarrow \tilde{g}\tilde{g}$). The cross section for this process falls steeply, from 214nb for $m_{\tilde{g}} = 20$ GeV/c² to 95 pb for $m_{\tilde{g}} = 70$ GeV/c², while the acceptance increases from $\sim 0.01\%$ for $m_{\tilde{g}} = 20$ GeV/c² to $\sim 3\%$ for $m_{\tilde{g}} = 70$ GeV/c². For gluino masses below 10 GeV/c², "indirect" gluino production $g \rightarrow \tilde{g}\tilde{g}$ (the dashed curve in figure 3(a)) becomes the dominant contribution.

For gluino masses below 20 GeV/c², rather tight cuts had to be placed on the generated events before passing them through the full simulation of the detector. A full evaluation of the expected event rate would have required a prohibitively large amount of computer time. For "direct" gluino production at $m_{\tilde{g}} = 7$ GeV/c² for example, the gluino transverse momentum was required to be greater than 20 GeV/c². Similarly, for "indirect" gluino production at $m_{\tilde{g}} = 7$ GeV/c², the transverse momentum of the gluon produced in the hard scatter was required to be greater than 30 GeV/c². (With these cuts, the acceptance varies from $\sim 10^{-5}$ to $\sim 10^{-4}$ for gluino masses between 4 GeV/c² and 20 GeV/c²). For $m_{\tilde{g}} < 20$ GeV/c² the event rates shown in figure 3(a) therefore significantly underestimate the true event rate. Further, we have not allowed for a possible K-factor

in the cross sections for direct or indirect gluino production (i.e. we have assumed $K=1$), and have not evaluated other gluino production processes such as scattering from the gluino content of the proton.

Figure 3(b) shows the predicted event rate as a function of squark mass for infinitely large gluino mass ($m_{\tilde{g}} \rightarrow \infty$). The event rate is dominated by direct squark pair production $\bar{p}p \rightarrow \tilde{q}\bar{q}$. The expected rate is similar to that for direct gluino production shown in figure 3(a). (The acceptance is a factor ~ 3 higher than for direct gluino pair production since the two body decay $\tilde{q} \rightarrow q\tilde{\gamma}$ gives a harder photino spectrum than the three body decay $\tilde{g} \rightarrow \bar{q}q\tilde{\gamma}$, but the squark production cross sections are smaller by a similar factor). Direct photino production $\bar{p}p \rightarrow \tilde{q}\tilde{\gamma}$ contributes approximately 20% of the total cross section as $m_{\tilde{g}} \rightarrow \infty$ [21]. However, this process produces mainly monojet events and contributes < 0.1 events to the total predicted rate shown in figure 3(b). We have not considered squark masses less than $20 \text{ GeV}/c^2$ since this region is excluded by e^+e^- data, though we would again expect significant contributions both from direct squark production and from indirect processes such as $g \rightarrow \tilde{q}\bar{q}$.

Expected event rates for selected values of squark and gluino mass are given in Table 1, together with the total production cross-sections and event acceptances (hardware trigger plus selection efficiency) measured from the Monte Carlo. The quoted errors on the predicted event rates are the statistical errors (typically 10-20%) resulting from the Monte Carlo generation. For squark and gluino masses greater than $40 \text{ GeV}/c^2$, the acceptance varies slowly with mass and lies between 1-10%. The acceptance is typically a factor ~ 3 higher for $m_{\tilde{g}} > m_{\tilde{q}}$ than for $m_{\tilde{g}} < m_{\tilde{q}}$, mainly because the latter case gives rise to events with higher jet multiplicities and correspondingly softer photinos.

The 90% C.L. limit contour on the squark mass as a function of the gluino mass is shown in figure 4. In computing this contour, we have taken into account all statistical and systematic errors on the data and on the Monte Carlo calculations. The mass limits improve significantly when the squark and gluino masses are similar (i.e. near the diagonal line in figure 4) since there is a large contribution from $\tilde{g}\bar{q}$ production in this region. For equal squark and gluino masses, we find that the squark (or gluino) mass must be greater than $75 \text{ GeV}/c^2$ at 90% C.L.. The shape of the 90% C.L. contour close to the diagonal line $m_{\tilde{g}} = m_{\tilde{q}}$ is difficult to determine precisely since the gluino

and squark decay branching fractions change relatively rapidly in this region. The contour shown is certainly conservative.

The asymptotic values of the 90% C.L. contour as the squark or gluino mass becomes infinitely large are indicated in figure 4 by the arrows on the vertical and horizontal axes. As $m_{\tilde{q}} \rightarrow \infty$, the total gluino production cross section remains approximately constant, and there is essentially no change in the limit on the gluino mass [22]. As $m_{\tilde{g}} \rightarrow \infty$ however, the $\tilde{q}\tilde{q}^*$ production cross section continues to fall [23] and the limit on the squark mass drops appreciably. Thus, the limit in which $m_{\tilde{g}} \rightarrow \infty$ ($m_{\tilde{q}} \rightarrow \infty$) allows us to set a limit on the squark (gluino) mass which is independent of the gluino (squark) mass. We find 90% C.L. limits on the squark and gluino mass of $m_{\tilde{q}} > 45 \text{ GeV}/c^2$ (independently of $m_{\tilde{g}}$) and $m_{\tilde{g}} > 53 \text{ GeV}/c^2$ (independently of $m_{\tilde{q}}$). Further, the total expected rate from direct plus indirect gluino production is sufficient to exclude gluinos down to a gluino mass of $4 \text{ GeV}/c^2$, independently of the assumed squark mass.

The systematic errors due to theoretical uncertainties in the perturbative QCD calculation of squark and gluino production cross sections (and in particular the uncertainties due to the choice of Q^2 scale and to higher order corrections) have not been taken into account[3]. A factor of two decrease in the computed cross sections for example would reduce the squark and gluino mass limits by $\sim 8 \text{ GeV}/c^2$. In addition, the region with gluino mass below $\sim 15 \text{ GeV}/c^2$ would only be excluded if the squark was light enough, $m_{\tilde{q}} < \sim 100 \text{ GeV}/c^2$. However, as mentioned above, the event rates computed from the Monte Carlo underestimate the true event rate in this light gluino region.

The limit on the gluino mass must be slightly qualified to take into account the effect of a finite gluino lifetime. For lifetimes longer than $\sim 10^{-10}$ seconds, a significant fraction of produced gluinos (confined in the form of supersymmetric hadrons) will reach the calorimeter before decaying. The missing energy signature might then be lost, and we cannot be certain that we would actually observe the full rate predicted above. We therefore conservatively leave open a window with gluino lifetime greater than 10^{-10} seconds (see figure 1). This corresponds to squark masses $m_{\tilde{q}} > \sim 1 \text{ TeV}/c^2$ for $m_{\tilde{g}} = 4 \text{ GeV}/c^2$, increasing to $m_{\tilde{q}} > \sim 30 \text{ TeV}/c^2$ for $m_{\tilde{g}} = 50 \text{ GeV}/c^2$ for example.

Finally, we consider the effect of a non-zero photino mass on the limits derived above. For

squark and gluino masses above $40 \text{ GeV}/c^2$, the expected event rate is not appreciably reduced until the photino mass becomes larger than $\sim 20 \text{ GeV}/c^2$, but then falls rapidly as the photino mass increases further. For a photino mass of $20 \text{ GeV}/c^2$ for example, the expected event rates are reduced by $\sim 10\%$, with a corresponding reduction in the squark and gluino mass limits of $\sim 2\text{--}3 \text{ GeV}/c^2$. For photino masses larger than this, the squark and gluino mass limits decrease rapidly. For the light gluino region, a finite photino mass increases the energy carried off by the photino[3], and hence improves the significance of the results above.

In summary, the sample of events with large missing transverse energy and two or more jets significantly constrains the allowed range of squark and gluino masses. Assuming the photino to be massless, we find 90% C.L. limits on the squark and gluino masses of $m_{\tilde{q}} > 45 \text{ GeV}/c^2$ (independently of $m_{\tilde{g}}$) and $m_{\tilde{g}} > 53 \text{ GeV}/c^2$ (independently of $m_{\tilde{q}}$), provided that the gluino is not long-lived (i.e. provided that the squark mass is not too heavy, $m_{\tilde{q}} < \sim 1 \text{ TeV}/c^2$). For equal squark and gluino masses, we find the limit $m_{\tilde{q}} = m_{\tilde{g}} > 75 \text{ GeV}/c^2$ at 90% C.L. These results are insensitive to photino masses of up to approximately $20 \text{ GeV}/c^2$.

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Table. 1. Production cross sections, experimental acceptances and predicted event rates from squark and gluino production ($\bar{p}p \rightarrow \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}, \tilde{g}\tilde{\gamma}, \tilde{q}\tilde{\gamma} + X$) for selected values of the squark and gluino mass. The errors quoted are the statistical errors resulting from the Monte Carlo generation.

$m_{\tilde{g}}$ (GeV/c ²)	$m_{\tilde{q}}$ (GeV/c ²)	cross section (nb)	acceptance (%)	events
30	200	20.20	0.2	24.0 ± 5.6
50	120	0.71	1.3	6.8 ± 0.8
50	90	0.78	1.4	7.7 ± 0.9
60	70	0.49	3.2	11.2 ± 0.8
70	90	0.11	2.5	2.0 ± 0.2
200	30	4.35	0.6	17.0 ± 2.2
120	50	0.44	3.8	12.0 ± 0.8
90	50	0.64	3.8	17.5 ± 1.2
70	60	0.49	6.0	20.9 ± 1.2
130	70	0.07	6.6	3.3 ± 0.2
90	70	0.13	7.0	6.5 ± 0.3
70	70	0.27	5.3	10.2 ± 0.8

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- a) no calorimeter jet with transverse energy >8 GeV (or central detector jet with $p_T > 5$ GeV/c) within ± 30 degrees in azimuth of the missing transverse energy direction, and
- b) no calorimeter jet with transverse energy >8 GeV (or central detector jet with $p_T > 5$ GeV/c) within ± 30 degrees in azimuth of the direction opposite to the highest transverse energy jet in the event.

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- [22] The gluino pair production cross section in fact increases with squark mass due to interference effects between diagrams with virtual gluon and virtual squark exchange. This increase is approximately compensated for by the fall in the cross sections for $\tilde{g}\tilde{q}$ and $\tilde{g}\tilde{g}$ production.
- [23] For $m_{\tilde{q}} = 50$ GeV/c² for example, the $\tilde{q}\tilde{q}$ production cross section falls by a factor ~ 3 between $m_{\tilde{g}} = 100$ GeV/c² and $m_{\tilde{g}} = 5000$ GeV/c².

FIGURE CAPTIONS

- Fig. 1.** Region of gluino and squark masses excluded (at 90% C.L.) by this analysis, together with the results from other experiments[7-11]. In addition, the dotted area (region III) is excluded by the NA3 experiment for certain assumptions on the gluino interaction cross section[9]. Regions I and II are not yet excluded by these experiments. Also shown are curves of equal gluino lifetime (see text).
- Fig. 2.** Distribution of $\Delta\phi$, the azimuthal angle between the two highest transverse energy jets in the event, for the large missing transverse energy event sample (histogram). The dashed curve shows the expectation for conventional (standard model) processes plus background, normalised to the data. The dot-dashed curve shows the $\Delta\phi$ distribution (multiplied by a factor 10) for squark and gluino production for a squark mass of 60 GeV/c² and a gluino mass of 70 GeV/c².
- Fig. 3.** Predicted contribution to the $\Delta\phi < 140^\circ$ multijet sample from supersymmetric particle production (a) as a function of gluino mass when the squark mass becomes infinitely large and (b) as a function of squark mass when the gluino mass becomes infinitely large. In (a), the dashed curve shows the contribution from "indirect" gluino production $\bar{p}p \rightarrow gX, g \rightarrow \tilde{g}\tilde{g}$.
- Fig. 4.** Limits (at 90% C.L.) on squark and gluino masses derived from the large missing transverse energy multijet sample. The arrows indicate the asymptotic values of the 90% C.L. contour as the squark or gluino mass becomes infinitely large. Also shown are the regions excluded by other experiments[6-11].

Fig. 1

Fig. 2

Fig. 3a

Fig. 3b

Fig. 4