EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/87-138

4 August 1987

**LIMITS ON THE MASSES OF SUPERSYMMETRIC PARTICLES
FROM UA1 EVENTS WITH LARGE MISSING TRANSVERSE ENERGY**

C. J. SEEZ

Imperial College, London

Representing the UA1 Collaboration

[Aachen–Amsterdam (NIKHEF)–Annecy (LAPP)–Birmingham–CERN–Harvard–
Helsinki–Kiel–Imperial College London–Queen Mary College London–Madrid–MIT–
Padua–Paris (College de France)–Riverside–Rome–Rutherford Laboratory–
Saclay (CEN)–Victoria–Vienna–Wisconsin]

Presented at the
2nd Topical Seminar on Heavy Flavour Physics,
San Miniato, Italy, 25–29 May 1987

LIMITS ON THE MASSES OF SUPERSYMMETRIC PARTICLES FROM UA1 EVENTS WITH LARGE MISSING TRANSVERSE ENERGY

C. J. SEEZ

Imperial College, London SW7, UK

Representing the UA1 Collaboration

[Aachen–Amsterdam (NIKHEF)–Annecy (LAPP) – Birmingham–CERN–Harvard–Helsinki–Kiel – Imperial College London – Queen Mary College London – Madrid – MIT – Padua – Paris (College de France) – Riverside – Rome – Rutherford Laboratory – Saclay (CEN) – Victoria – Vienna – Wisconsin]

A sample of events with large missing transverse energy, taken in the UA1 detector and representing an integrated luminosity of 715 nb^{-1} , is used to set limits on the masses of squarks and gluinos. We find $m_{\tilde{q}} > 45 \text{ GeV}/c^2$ at 90% CL, independent of the gluino mass, and $m_{\tilde{g}} > 53 \text{ GeV}/c^2$ independent of squark mass, provided that the gluino is not long-lived. If $m_{\tilde{q}} = m_{\tilde{g}} = m$ we find $m > 75 \text{ GeV}/c^2$.

1. INTRODUCTION

In most supersymmetric models the supersymmetric partners of quarks and gluons, squarks and gluinos, should be produced in proton–antiproton collisions with cross-sections^{1–3} which are calculable in QCD and range from 100 pb to 100 nb for squark and gluino masses between 20 and 70 GeV/c^2 . The squarks and gluinos will then decay into photinos (assuming the photino to be the lightest supersymmetric particle) and two or more quarks. The photino, having a negligible interaction cross-section, will be undetected, resulting in a signature of missing energy and some number of jets (this assumes a stable or quasi-stable photino, i.e. conservation of R-parity). We have looked for such a signature in the UA1 data.

2. THE DATA

The data analysed were taken in the UA1 detector in 1983–85 and represent an integrated luminosity of 715 nb^{-1} (118 nb^{-1} at $\sqrt{s} = 546 \text{ GeV}$ and 597 nb^{-1} at $\sqrt{s} = 630 \text{ GeV}$). The data were selected according to the following criteria:

- i) $E_T^{\text{miss}} > 15 \text{ GeV}$ and $N_{\sigma} > 4$, where N_{σ} is defined as $E_T^{\text{miss}} / (0.7\sqrt{\Sigma E_T})$; ΣE_T is the scalar sum of transverse-energy deposits observed in the calorimeter cells measured in GeV; N_{σ} is thus a measure of the significance of observed missing transverse energy;
- ii) two or more jets⁴ observed in the calorimeters with $E_T > 12 \text{ GeV}$ and $|\eta| < 2.5$;
- iii) validation of the highest E_T jet by a track with $p_T > 1 \text{ GeV}/c$ within a cone of size $\Delta R = 0.4$ centred on the jet axis ($\Delta R^2 \equiv \Delta\phi^2 + \Delta\eta^2$, where ϕ is azimuthal angle and η pseudorapidity);

- iv) veto of events containing an electron or muon candidate;
- v) veto of events having the characteristics of $W \rightarrow \tau\nu$, $\tau \rightarrow \text{hadrons} + \nu$ by requiring that the relative τ log-likelihood⁵, L_τ^{-1} satisfies $L_\tau < 0$;
- vi) removal of events having a back-to-back topology by requiring that the azimuthal angle between the two highest transverse-energy jets be less than 140° .

Additional technical cuts were applied to remove events due to backgrounds such as cosmic rays, beam halo, and double interactions. The events remaining after these cuts were all scanned on an interactive graphics facility to check that the observed missing energy was not due to spurious background or detector-reconstruction problems: no such cases were found. A total of 4 events passed all the above selection criteria.

The selection criteria used are the same as those described in our two published papers on events with large missing transverse energy⁵ except that the requirement of $\Delta\phi < 140^\circ$ between the two highest E_T jets replaces the previous cuts against back-to-back topologies. A cut against such topologies is necessary to remove events with large apparent E_T^{miss} resulting from a fluctuation of calorimeter response to a two-jet event. Figure 1 shows the distribution in $\Delta\phi$ of the selected events before the application of the final $\Delta\phi < 140^\circ$ cut. It can be seen that there is an accumulation of events towards $\Delta\phi = 180^\circ$.

Essentially similar results to those presented below can be derived with the selection used in the published papers, using the multijet sample when considering high squark and gluino masses and using the full (monojet and multijet) sample for the case of light gluinos ($m_{\tilde{g}} < 20 \text{ GeV}/c^2$). However, the $\Delta\phi < 140^\circ$ multijet selection described above has the advantage that it can be used to cover the complete range of squark and gluino masses.

FIGURE 1
Azimuthal angle between the two highest transverse-energy jets in each event, $\Delta\phi$, for data (histogram), Monte Carlo of standard model processes (solid curve), and for squark pair production at $m_{\tilde{q}} = 60 \text{ GeV}/c^2$. The curves are arbitrarily normalized.

3. STANDARD MODEL BACKGROUND

We have evaluated the expected contribution to our final selected sample from Standard Model processes using the ISAJET Monte Carlo program⁶ together with a full simulation of the UA1 detector including hardware triggers. The parameters controlling the production of spectator particles in ISAJET have been adjusted to give distributions consistent with those measured by UA1. Similarly, the transverse-momentum distributions of the W and Z bosons produced by ISAJET have been adjusted to agree with those measured.

The background due to jet fluctuations has been evaluated with a separate Monte Carlo technique which uses UA1 jet data⁵.

The total predicted number of events passing all the selection criteria is $5.2 \pm 1.9 \pm 1.0$, in good agreement with the observed 4 events. A breakdown of the various contributions to this number is shown in Table 1.

Table 1

Predicted number of events passing all selection criteria from Standard Model processes, together with statistical and systematic errors

W/Z processes (excluding τ)	$1.17 \pm 1.02 \pm 0.23$
Heavy flavour (b and c) processes	$1.98 \pm 0.84 \pm 1.01$
$\tau \rightarrow$ hadrons	$1.87 \pm 0.80 \pm 0.34$
Jet fluctuations	$0.14 \pm 0.13 \pm 0.04$
TOTAL	$5.2 \pm 1.9 \pm 1.0$

4. THE SUPERSYMMETRY MODEL

In order to determine the expected rates of events from squark and gluino production passing these selection criteria, we again used the ISAJET Monte Carlo program, with full simulation of the UA1 detector.

For most of the investigation we have taken the mass of the photino to be zero, but we have made a study of the effect on our final results of a non-zero photino mass which will be discussed below. We have taken five mass-degenerate squarks and ignored processes involving the supersymmetric partners of the W, Z, and leptons. The model used thus has two free parameters: $m_{\tilde{g}}$ and $m_{\tilde{q}}$.

We have only considered squark masses greater than $20 \text{ GeV}/c^2$ because of the existence of limits from e^+e^- experiments⁷ ($m_{\tilde{q}} > 21.5 \text{ GeV}/c^2$), and gluino masses greater than $4 \text{ GeV}/c^2$ because of the existence of a limit from a BEBC beam-dump experiment ($m_{\tilde{g}} > 3\text{--}4 \text{ GeV}/c^2$ depending on the squark mass⁸).

Events were generated for a wide range of squark and gluino masses and passed through the same selection programs as the data. All hard scattering processes of order α_s^2 ($p\bar{p} \rightarrow \tilde{g}\tilde{g}$, $\tilde{q}\bar{q}$, $\tilde{g}\tilde{q}$) and $\alpha\alpha_s$ ($p\bar{p} \rightarrow \tilde{g}\tilde{\gamma}, \tilde{q}\tilde{\gamma}$) were included in the calculation, which uses the matrix elements

given in Ref. 2. Gluon bremsstrahlung from initial- and final-state partons (including squarks and gluinos) is included in the ISAJET program. Squarks and gluinos are decayed according to two- or three-body phase space, and the quarks from these decays fragmented according to the Field-Feynman independent fragmentation model. The decay modes used are taken from Ref. 1, and are as follows:

$$\text{If } m_{\tilde{g}} > m_{\tilde{q}} \text{ then: } \tilde{q} \rightarrow q\tilde{\gamma}, \quad \tilde{g} \rightarrow \bar{q}q,$$

$$\text{and if } m_{\tilde{q}} > m_{\tilde{g}} \text{ then: } \tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$$

$$\tilde{q} \rightarrow q\tilde{g} \quad \text{branching ratio } r/(1+r)$$

$$\tilde{q} \rightarrow q\tilde{\gamma} \quad \text{branching ratio } 1/(1+r) \text{ where } r = (\alpha_s/\alpha e_q^2)(1 - m_{\tilde{g}}^2/m_{\tilde{q}}^2)^2 \text{ *).$$

Expected event rates for selected values of squark and gluino masses are given in Table 2, together with the total production cross-sections and event acceptances (hardware trigger plus selection efficiency) measured by the Monte Carlo. The errors shown are the statistical errors (typically 10-20%) of the Monte Carlo generation. For squark and gluino masses greater than 40 GeV/c² the acceptance varies slowly with mass, and is typically a factor ≈ 3 higher for $m_{\tilde{g}} > m_{\tilde{q}}$ than for $m_{\tilde{q}} > m_{\tilde{g}}$ because the latter case gives rise to a larger number of quarks in the final state and correspondingly softer photinos.

The main characteristics of the predictions from the supersymmetry model can be most easily seen by considering the two limiting cases: a) where the gluino mass becomes large so that $\tilde{q}\bar{\tilde{q}}$ production dominates, and b) where the squark mass is large and $\tilde{g}\tilde{g}$ production dominates.

Table 2

Predicted event rates, production cross-sections, and experimental acceptances from supersymmetric particle production for selected values of squark and gluino mass

$m_{\tilde{g}}$ (GeV/c ²)	$m_{\tilde{q}}$ (GeV/c ²)	Cross-section (nb)	Acceptance (%)	Events
30	200	20.2	0.2	24.0 $\pm$ 5.6
50	120	0.71	1.3	6.8 $\pm$ 6.8
50	90	0.78	1.4	7.7 $\pm$ 0.9
60	70	0.49	3.2	11.2 $\pm$ 0.8
70	90	0.11	2.5	2.0 $\pm$ 0.2
200	30	4.35	0.6	17.0 $\pm$ 2.2
120	50	0.44	3.8	12.0 $\pm$ 0.8
90	50	0.64	3.8	17.5 $\pm$ 1.2
70	60	0.49	6.0	20.9 $\pm$ 1.2
130	70	0.07	6.6	3.3 $\pm$ 0.2
90	70	0.13	7.0	6.5 $\pm$ 0.3
70	70	0.27	5.3	10.2 $\pm$ 0.8

*) In Ref. 1 there is an error in the formula for the squark decay width given in Eq. (A.31) ($m_{\tilde{g}}$ should read $m_{\tilde{\gamma}}$) and in the expression for r accompanying Eq. (3.18).

FIGURE 2

Predicted number of events passing all selection cuts from the supersymmetry Monte Carlo, a) as a function of squark mass as the gluino mass becomes infinitely large, and b) as a function of gluino mass as the squark mass becomes infinitely large. The dashed curve in b) shows the contribution from indirect gluino production.

Figure 2a) shows the predicted event rate from our supersymmetry model for infinitely large gluino mass. The event rate is dominated by $\tilde{q}\tilde{q}$ production. Although $p\bar{p} \rightarrow \tilde{q}\tilde{q} + X$ accounts for 20% of the cross-section as $m_{\tilde{g}} \rightarrow \infty$ it contributes less than 0.1 events to the total predicted rate because of the requirement that there be two or more jets in the event. It can be seen that the event rate drops away with increasing squark mass as the cross-section falls. As the mass of the squark is decreased the resulting E_T^{miss} spectrum softens, both because the production p_T spectrum of the squarks softens and because the photinos resulting from the decay of a lighter squark tend to be more back-to-back in azimuth. The acceptance of our selection criteria thus falls. It can be seen that the fall in acceptance begins to win over the increasing cross-section as $m_{\tilde{q}}$ falls below $\approx 30 \text{ GeV}/c^2$.

Figure 2b shows the predicted event rate for infinitely large squark mass. For large gluino masses the rate is dominated by direct gluino pair production ($p\bar{p} \rightarrow \tilde{g}\tilde{g}$). For this process, as in the case of $\tilde{q}\tilde{q}$ production, the falling acceptance starts to win over the rising cross-section as the mass falls below $\approx 30 \text{ GeV}/c^2$, and the resulting event rate would not allow us to exclude the existence of light gluinos. We have, however, also evaluated the contribution from 'indirect' gluino pair production, $p\bar{p} \rightarrow gX, g \rightarrow \tilde{g}\tilde{g}$, where a gluon from a standard-model QCD hard-scattering diagram fragments into a $\tilde{g}\tilde{g}$ pair. Such a fragmentation was implemented in ISAJET using the Altarelli-Parisi evolution function given by Jones and Llewellyn-Smith⁹. Figure 2b shows the contribution from this process as a dashed curve.

For gluino masses below $20 \text{ GeV}/c^2$, the existence of large cross-sections and small acceptances makes the evaluation of the expected event rates difficult. Tight cuts had to be placed on the generated events before passing them through the detector simulation, since a full evaluation would require a prohibitively large amount of computer time. Also, we have not

evaluated the contribution to $\tilde{g}$ production from diagrams involving the excitation of gluinos in the proton sea. The event rates shown in Fig. 2b for $m_{\tilde{g}} < 20 \text{ GeV}/c^2$ thus significantly underestimate the true rate.

5. RESULTS

The 90% CL limit on the squark mass as a function of gluino mass is shown in Fig. 3. We find $m_{\tilde{q}} > 45 \text{ GeV}/c^2$ (independently of $m_{\tilde{g}}$) and $m_{\tilde{g}} > 53 \text{ GeV}/c^2$ (independently of $m_{\tilde{q}}$) at the 90% CL. If $m_{\tilde{q}} = m_{\tilde{g}} = m$ we find $m > 75 \text{ GeV}/c^2$ at 90% CL. In computing these limits we have taken into account all statistical and systematic errors on the data and the Monte Carlo calculations, and have allowed for the fact that the Standard Model background cannot have exceeded the observed number of events (i.e. four). As $m_{\tilde{g}} \rightarrow \infty$ the $p\bar{p} \rightarrow \tilde{q}\bar{\tilde{q}}$ cross-section continues to drop; thus the limit on $m_{\tilde{q}}$ independent of $m_{\tilde{g}}$ is somewhat below the value of $m_{\tilde{q}}$ where the contour cuts the right-hand axis of Fig. 3.

FIGURE 3
Limits (at 90% CL) on squark and gluino masses. The arrows indicate the asymptotic values of the 90% CL contour.

The limit on the gluino mass must be slightly qualified to take into account the effect of the gluino lifetime. For lifetimes longer than $\approx 10^{-10} \text{ s}$, a significant fraction of produced gluinos will reach the calorimeter before decaying (presumably in the form of some bound state), resulting in a loss of the E_T^{miss} signature. Figure 4 shows the 10^{-10} s lifetime contour as a function of the squark and gluino masses. It can be seen that requiring $\tau_{\tilde{g}} < 10^{-10} \text{ s}$ corresponds to $m_{\tilde{q}} < 2 \text{ TeV}/c^2$ for $m_{\tilde{g}} = 7 \text{ GeV}/c^2$, for example.

Concerning the possibility of a non-zero photino mass we find that the predicted event rate is not appreciably reduced until $m_{\tilde{\gamma}}$ becomes larger than $\approx 25 \text{ GeV}/c^2$, after which it drops rapidly. For a photino mass of $20 \text{ GeV}/c^2$, for example, the expected event rates are reduced by $\approx 10\%$, corresponding to a reduction in the squark and gluino mass limits of $\approx 2\text{--}3 \text{ GeV}/c^2$.

FIGURE 4

Contours of gluino lifetime as a function of squark and gluino mass. Also shown are the regions excluded by a BEBC beam-dump experiment⁸, and by stable particle searches¹⁰.

* * *

REFERENCES

- 1) R. Barnett, H. Haber and G. Kane, Nucl. Phys. **B267** (1986) 625.
- 2) S. Dawson, E. Eichten and C. Quigg, Phys. Rev. **D31** (1985) 1581.
- 3) J. Ellis and H. Kowalski, Nucl. Phys. **B259** (1985) 109.
E. Reya and D. Roy, Phys. Lett. **166B** (1986) 223.
- 4) G. Arnison et al., Phys. Lett. **132B** (1983) 214.
- 5) C. Albajar et al., Phys. Lett. **185B** (1987) 233 and 241.
- 6) F. Paige and S. Protopopescu, ISAJET program version 5.20, BNL38034 (1986).
- 7) B. Naroska, Phys. Rep. **148** (1987) 67.
H.-J. Berend et al., DESY preprint 87-013 (1987).
- 8) A. Cooper-Sarkar et al., Phys. Lett. **166B** (1985) 212.
- 9) S. Jones and C. Llewellyn-Smith, Nucl. Phys. **B217** (1983) 145.
- 10) B. Alper et al., Phys. Lett. **46B** (1973) 265.
D. Cutts et al., Phys. Rev. Lett. **41** (1978) 363.