Multijet events with missing transverse momentum from scalar-quark pair production at the CERN $p\bar{p}$ collider

V. Barger
Physics Department, University of Wisconsin, Madison, Wisconsin 53706

K. Hagiwara
Theory Group, DESY, D-2000 Hamburg 52, Federal Republic of Germany

W.-Y. Keung
Physics Department, University of Illinois, Chicago, Illinois 60680

R. J. N. Phillips
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon 0X11 0QX, England

J. Woodside
Physics Department, University of Wisconsin, Madison, Wisconsin 53706

(Received 28 January 1985)

Predictions of the scalar-quark-pair-production scenario, proposed to explain monojets observed at the CERN $p\bar{p}$ collider, are extended to multijets with missing p_T. The n-jet cross sections are calculated from lowest-order subprocesses as functions of scalar-quark and gluino masses. Predictions are made for azimuthal correlations $\Delta\phi$, pseudorapidity correlation $\Delta\eta$, and a jet transverse-momentum asymmetry in dijet events.

After the UA1 collaboration reported[1] the observation of monojet events with large missing transverse momentum ($\not{p}_T$) at the CERN $p\bar{p}$ collider, several models[2–6] based on supersymmetry were proposed to explain the data. Supersymmetry (SUSY) naturally leads to events with $\not{p}_T$ since the photino ($\tilde{\gamma}$), which is produced in $\tilde{q}$ or $\tilde{g}$ decays and is supposed to be stable, interacts feebly and is thereby undetected in collider experiments. A common feature of the supersymmetric interpretations is the prediction of $\not{p}_T$ events with multijets at differing rates.[6] The UA1 collaboration has just reported[7] the observation of dijet and monojet events with large $\not{p}_T$ (>40 GeV) from the new run at $\sqrt{s}=630$ GeV. Also, a trijet event with large $\not{p}_T$ was found[1] in the previous run at $\sqrt{s}=540$ GeV. With future more detailed information from multijet events, it should soon be possible to more closely define the permissible range of SUSY-particle masses that can describe the observed $\not{p}_T$ events. The new data motivates a more detailed study of the predictions of the various supersymmetry scenarios, all of which have a light photino (<20 GeV).

The three SUSY scenarios advocated in previous studies are the following: (A) scalar-quark-pair production with $\tilde{q}\to q\tilde{\gamma}$ decay: $m(\tilde{g})>m(\tilde{q})\sim 40$ GeV; (B) gluino pair production with $\tilde{g}\to q\bar{q}\tilde{\gamma}$ decay: $m(\tilde{q})>m(\tilde{g})\sim 40$ GeV; and (C) single extra-heavy-scalar-quark production, from[4] $qg\to\tilde{q}\tilde{g}$ or from[5] $q\tilde{g}\to\tilde{q}$ subprocesses, with a light gluino and $\tilde{q}\to q\tilde{\gamma}$ decay; $m(\tilde{q})\sim 100$ GeV, $m(\tilde{g})\sim 3$–10 GeV. In each scenario the missing p_T is ascribed to decay photinos. In C, gluino pair production does not contribute importantly to large $\not{p}_T$ because of soft $\tilde{g}$ fragmentation.[8] Scenario B is disfavored[6] because it gives rather broad monojets and a soft $\not{p}_T$ spectrum, unlike present indications from the data. Scenario C gives the hardest p_T spectrum, from the Jacobian peak in the two-body heavy-scalar-quark decay, for which there may be some preference from the observed monojet $\not{p}_T$ spectrum. However, C gives a rather low dijet-to-monojet ratio[6] of order $\frac{1}{5}$. Because of the possibility that dijets may be more plentiful than previously indicated (the analysis of the first data set may have been biased against detection of dijets[7]), we concentrate our attention here on a more detailed examination of scenario A.

As in previous calculations, we assume that the $\tilde{\gamma}$ and $\tilde{g}$ couplings are flavor diagonal and that the scalar-quark mass spectrum is approximately mass degenerate for five flavors and two chiralities; scalar-quark masses below 22 GeV are excluded by e^+e^- annihilation experiments.[9] We neglect the photino mass in $\tilde{q}\to q\tilde{\gamma}$ decay calculations. Simple grand unification schemes[10] give the mass relation

$$m_{\tilde{\gamma}}/m_{\tilde{g}}\leq 8\alpha/[3\alpha_s(m_{\tilde{g}})]\approx\tfrac{1}{7}$$

in the absence of significant mixing in the neutral-gauge/Higgs-fermion sector. A photino mass of this order would affect our analysis only for limited ranges of the $m_{\tilde{q}},m_{\tilde{g}}$ masses of interest. The cross sections are calculated from the order-$\alpha_s{}^2$ QCD subprocesses $q\bar{q},gg\to\tilde{q}\bar{\tilde{q}},\tilde{g}\tilde{g}$ and $qg\to\tilde{q}\tilde{g}$ following Ref. 6; contributions from gluino decays $\tilde{g}\to\bar{\tilde{q}}q,\tilde{q}\bar{q}$ are taken into account. Final states produced by these subprocesses and subsequent $\tilde{q}\to q\tilde{\gamma}$ decays contain two photinos and from two to four quarks, giving missing p_T and up to four jets.

Jets are defined by an algorithm[6] that approximates that of the UA1 collaboration. Quarks with momenta that satisfy

$$[(\Delta\eta)^2+(\Delta\phi)^2]^{1/2}<1\ ,$$

where $\Delta\eta$ is the pseudorapidity difference and $\Delta\phi$ is the az-

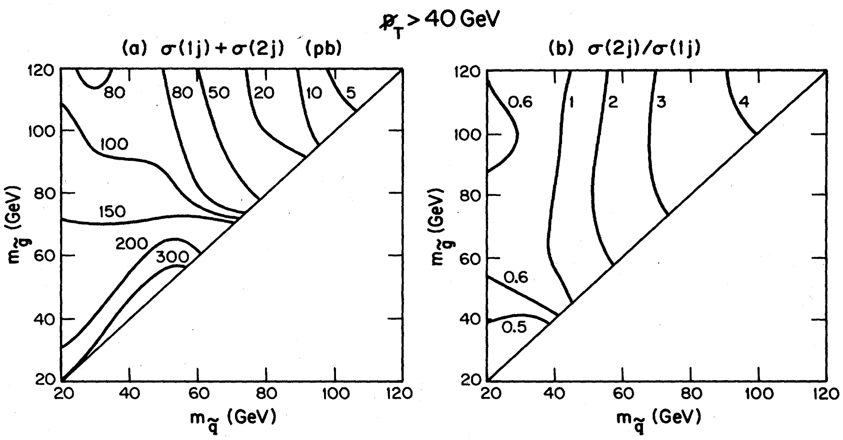

FIG. 1. Predictions of the scalar-quark-pair scenario for σ(n-jet) cross sections with $\not{p}_T > 40$ GeV, vs scalar-quark and gluino masses. (a) $\sigma(1j)+\sigma(2j)$; (b) $\sigma(2j)/\sigma(1j)$. A branching fraction $B(\tilde{q}\to q\tilde{\gamma})=1$ is assumed here.

imuthal angle difference between them, are coalesced in clusters which are identified as jets provided that

$$p_T(j)=|\sum_i \mathbf{p}_{Ti}|>25 \text{ GeV}$$

for the leading jet (j_1) and $p_T(j)>12$ GeV for any remaining jets ($j_2, j_3, \ldots$).

Figure 1(a) shows cross-section predictions at $\sqrt{s}=630$ GeV, summed over monojet and dijet events with $\not{p}_T > 40$ GeV, assuming $B(\tilde{q}\to q\tilde{\gamma})=1$. The results are presented as contours of constant cross sections in a plane with axes $m_{\tilde{q}}$ and $m_{\tilde{g}}$. The cross sections are calculated with a K factor of 1, and allowance must be made for the possibility of an enhancement factor of order 2. The cross-section values at $\sqrt{s}=540$ GeV can be approximately obtained by multiplying the results in Fig. 1(a) by 0.6.

We can attempt to estimate the cross section from the eight events at $\sqrt{s}=630$ GeV with $\not{p}_T > 40$ GeV for the analyzed luminosity of $\int \mathscr{L}dt = 0.13$ pb^{-1}. Assuming a detection efficiency ϵ of order 0.5, and a decay branching fraction $B(\tilde{q}\to q\tilde{\gamma})>0.7$, whose precise value depends[11] on the lowest charged gauge/Higgs-fermion ($\tilde{\omega}$) mass, we obtain

$$\sum_{n=1,2}\sigma(n\text{-jet})=N/\left[B^2\epsilon\int\mathscr{L}\,dt\right]\approx 200\pm 100 \text{ pb} \quad (1)$$

From Fig. 1(a), with $K=1$, cross sections of this order are obtained for $m_{\tilde{q}} \lesssim 70$ GeV.

Figure 1(b) gives the predicted dijet-to-monojet ratio for $\not{p}_T > 40$ GeV. Assuming that the numbers of dijets and monojets observed in the more recent run implies that $\sigma(1j)/\sigma(2j)<2$, we infer the bound

$$m_{\tilde{q}} \lesssim 55 \text{ GeV} \quad . \quad (2)$$

This restriction is independent of a possible K factor.

The predicted trijet event rate for $\not{p}_T > 40$ GeV relative to the sum of monojets and dijets is rather insensitive to $\tilde{q}$ and $\tilde{g}$ masses. For $m_{\tilde{g}} \lesssim 100$ GeV, the result is in the range

$$\sigma(3j)/[\sigma(1j)+\sigma(2j)]\approx 0.08\text{–}0.16 \quad . \quad (3)$$

The one observed three-jet event[1] with $\not{p}_T \simeq 51$ GeV is consistent with this expectation. Since QCD radiation (incident-parton bremsstrahlung, etc.) may add additional jets at the 10% level, the three-jet rate calculated from $\tilde{q}$ and $\tilde{g}$ decays alone is to be regarded as a lower limit only.

Figure 2 shows the predicted $\not{p}_T$ distributions (>20 GeV) at $\sqrt{s}=630$ GeV for one-, two-, and three-jet events with the SUSY-particle mass choices $m_{\tilde{q}}, m_{\tilde{g}} = (45,70)$ and (55,70) in GeV units. The distributions obtained at $\sqrt{s}=540$ GeV are rather similar to these. The arrows along the top of the figure denote the data values of the UA1 monojet events at $\sqrt{s}=630$ GeV with $p_T > 40$ GeV; the initial monojet data at $\sqrt{s}=540$ GeV are denoted by asterisks. We make the following observations about the results.

(i) The n-jet $\not{p}_T$ distributions fall rapidly with increasing $\not{p}_T$ beyond $\not{p}_T = m_{\tilde{q}}$. Two photinos, each with Jacobian peaks at $\frac{1}{2}m_{\tilde{q}}$, can easily add up to give $\not{p}_T \simeq m_{\tilde{q}}$, but not much higher $\not{p}_T$.

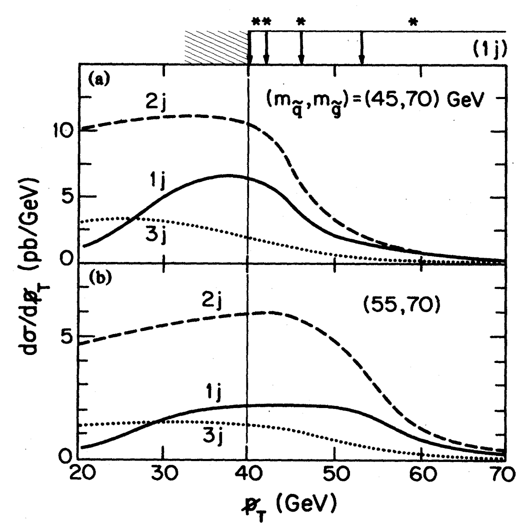

FIG. 2. Predicted $\not{p}_T$ distributions of one-, two-, and three-jet events in the scalar-quark-pair scenario, for the ($m_{\tilde{q}}, m_{\tilde{g}}$) choices (a) (45,70), (b) (55,70), in GeV units. The arrows along the top denote $\not{p}_T$ values of the more recent UA1 monojet events (the asterisks label $\not{p}_T$ values of monojet events from the earlier run); see Refs. 1 and 7.

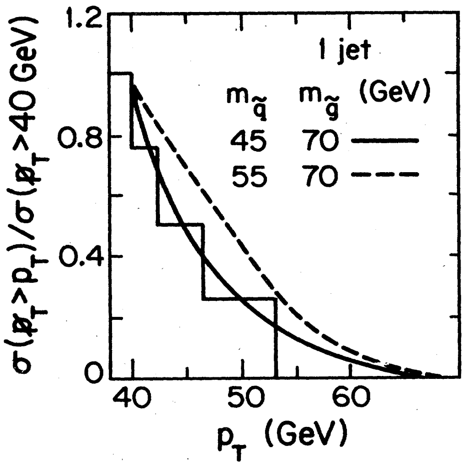

FIG. 3. Cumulative monojet cross sections with $\not{p}_T > p_T$ for the SUSY-particle mass choices of Fig. 2, compared with the recent UA1 data from Ref. 7.

(ii) The $\not{p}_T$ distributions are consistent with a scalar-quark mass of order 45–55 GeV. For scalar-quark masses in this range, $\sigma(2j)/\sigma(1j) \sim 2$ for $\not{p}_T > 40$ GeV.

(iii) The $\not{p}_T$ distributions are insensitive to the choice of gluino mass, which we have chosen relatively low to have a larger $\sigma(1j)+\sigma(2j)$ cross section.

Comparisons of the predicted $\not{p}_T$ distributions with the present low-statistics data are more meaningful for the cumulative cross section, $\sigma(\not{p}_T > p_T)$, integrated over $\not{p}_T > p_T$. Figure 3 shows this comparison with the more recent UA1 monojet data.

Further tests of the scalar-quark-pair scenario are possible based on correlations in dijet events. Interesting correlation variables are the azimuthal angular differences $\Delta\phi(j_1 j_2)$ and $\Delta\phi(j_1 \not{p}_T)$, the pseudorapidity difference $\Delta\eta = |\eta(j_1) - \eta(j_2)|$, and the transverse-momentum asymmetry between the two jets,

$$a \equiv p_T(j_2)/p_T(j_1) \quad . \tag{4}$$

Predictions of these correlations are given in Fig 4.

The scalar-quark-pair scenario predicts dijets with the following features.

(i) $|\Delta\phi(j_1 \not{p}_T)| > 120°$ almost always.

(ii) Broad $\Delta\phi(j_1 j_2)$ distribution; about three quarters of events fall between 40° and 140°.

(iii) Preference for small $\Delta\eta(j_1,j_2)$; about half the dijets have $|\Delta\eta| < 1$.

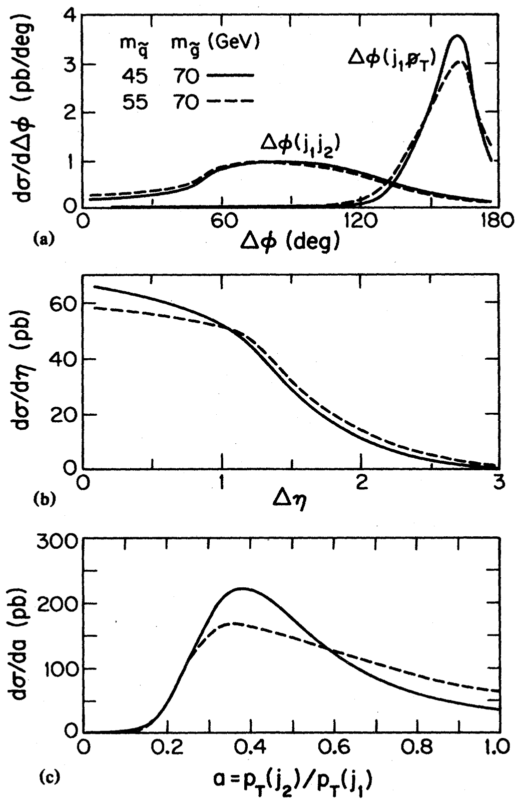

FIG. 4. Predicted correlations in dijet events at $\sqrt{s} = 630$ GeV. (a) Azimuthal difference between the two jets, $\Delta\phi(j_1,j_2)$ and azimuthal difference between the fast jet and the missing $\not{p}_T$, $\Delta\phi(j_1,\not{p}_T)$; (b) pseudorapidity difference $\Delta\eta(j_1,j_2)$ between the two jets; and (c) transverse-energy asymmetry defined by Eq. (4). The SUSY-particle mass choices $(m_{\tilde{q}},m_{\tilde{g}}) = (45,70)$ and (55,70) GeV are illustrated.

(iv) A momentum asymmetry between the jets that has a broad enhancement near $p_T(j_2)/p_T(j_1) \simeq 0.4$ (and little contribution below 0.2 due to the cuts).

We thank H. Baer, H. Haber, G. Kane, and M. Mohammadi for discussions. One of us (W.-Y.K.) thanks Fermilab for use of research facilities. This research was supported in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation, and in part by the Department of Energy under Contracts No. DE-AC02-76ER00881 and No. DE-FG02-84ER40173.

[1]UA1 collaboration, G. Arnison *et al.*, Phys. Lett. **139B**, 115 (1984).

[2]V. Barger, K. Hagiwara, and W.-Y. Keung, Phys. Lett. **145B**, 147 (1984); J. Ellis and H. Kowalski, Nucl. Phys. **B246**, 189 (1984); A. R. Allan, E. W. N. Glover, and A. D. Martin, Phys. Lett. **146B**, 247 (1984); see also H. E. Haber and G. L. Kane, *ibid.* **142B**, 212 (1984).

[3]E. Reya and D. P. Roy, Phys. Lett. **141B**, 442 (1984); Phys. Rev. Lett. **52**, 881 (1984); J. Ellis and H. Kowalski, Phys. Lett. **142B**, 441 (1984).

[4]V. Barger, K. Hagiwara, W.-Y. Keung, and J. Woodside, Phys. Rev. Lett. **53**, 641 (1984).

[5]M. J. Herrero, L. E. Ibáñez, C. López, and F. J. Yndurain, Phys. Lett. **132B**, 199 (1984); **145B**, 430 (1984); M. Barnett, H. Haber, and G. Kane, Phys. Rev. Lett. **54**, 1983 (1985).

[6]V. Barger, K. Hagiwara, W.-Y. Keung, and J. Woodside, Phys. Rev. D **31**, 528 (1985); V. Barger, University of Wisconsin Report No. MAD/PH/229, 1984 (unpublished); talk at meeting of the APS division of Particles and Fields, Sante Fe, 1984 (unpublished).

[7]UA1 collaboration, M. Mohammadi, talk at Aspen Winter Confer-

ence, 1985 (unpublished); C. Rubbia, talk at Rutherford meeting, 1984 (unpublished).
[8]V. Barger, K. Hagiwara, S. Jacobs, and J. Woodside, University of Wisconsin Report No. PH1232, 1985 (unpublished).
[9]S. Wagner, talk at meeting of the APS Division of Particles and Fields, Sante Fe, 1984 (unpublished).
[10]C. Kounnas, A. B. Lahanas, D. V. Nanopoulos, and M. Quirós, Phys. Lett. **132B**, 95 (1983); Nucl. Phys. **B236**, 438 (1984); J. Ellis, K. Enquist, D. Nanopoulos, and K. Tanivakis, CERN Report No. 4108, 1985 (unpublished).
[11]V. Barger, W.-Y. Keung, and R. J. N. Phillips, Phys. Rev. Lett. **55**, 166 (1985).