Prospects for supersymmetry at the Fermilab collider

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We compute cross sections for production of pairs of strongly interacting supersymmetric (SUSY) particles in $p\bar{p}$ collisions as a function of collider energy. For a scalar-quark or gluino mass of 80 GeV, we find that the ratio of the SUSY cross section to the standard-model background increases by a factor of about 10 when $\sqrt{s}$ is increased from 630 to 1600 GeV. If decays to photinos are dominant, we show that in the first 2 years of running, experiments at the Fermilab Tevatron collider should be sensitive to gluino (scalar-quark) masses up to at least $m_{\tilde{g}}=150$ GeV ($m_{\tilde{q}}=120$ GeV). We show characteristic missing-p_T distributions expected if SUSY particles with such masses are produced. For SUSY particles of large mass, we stress the importance of scalar-quark and gluino decays to W and Z gauginos.

I. INTRODUCTION

Supersymmetry (SUSY) as a symmetry of nature intrigues many physicists as a solution to the hierarchy problem, as a possible path towards unification with gravity, and as an aesthetically appealing symmetry not yet observed at the level of elementary-particle interactions.[1] Confirmation of its existence can come only through the observation of supersymmetric particles, which have yet to be seen.[2] Recently, interest has focused on the possibility of searching for strongly interacting supersymmetric particles—scalar quarks ($\tilde{q}$) and gluinos ($\tilde{g}$)—at the CERN $p\bar{p}$ collider.[3–5] The signature for these SUSY particles is the presence in an event of one or more hadronic jets accompanied by large amounts of *missing* transverse momentum $\not{p}_T$. The missing transverse momentum is carried off by weakly interacting photinos produced in the decay of the scalar quarks or gluinos.

The report[6] in 1984 by the CERN UA1 collaboration of five monojet events with anomalously large $\not{p}_T$ led to hopes that the discovery of strongly interacting SUSY particles (SISP's) was imminent.[7] Subsequently, detailed calculations of $\not{p}_T$ spectra from the decays of the intermediate vector bosons $W^{\pm}$ and Z^0 showed that the monojet sample was not inconsistent with standard-model backgrounds.[8] In a later run of the UA1 experiment a smaller number of events with $\not{p}_T$ was observed per unit of integrated luminosity.[9] The small number of events with $\not{p}_T$ in the accumulated CERN collider data sample was used by several groups to establish limits on the masses of scalar quarks and gluinos,[4,5] ranging from $m_{\tilde{g}}>60$ GeV to $m_{\tilde{g}}>80$ GeV, and $m_{\tilde{q}}>65$ GeV to $m_{\tilde{q}}>80$ GeV, depending upon the selection made of events with $\not{p}_T$ and the specific event generator used. Because of the sharp decrease of cross section with the mass of the SISP's at a given collider energy, it is doubtful the CERN UA1 and UA2 Collaborations will be able to push these limits much beyond their present values. However, the successful operation of the Fermilab $p\bar{p}$ collider at $\sqrt{s}=1.6$ TeV (to be extended to 2 TeV) encourages hope of extending the search for SISP's to a much higher mass region.

In this paper, we study the cross sections for producing SISP's at the Fermilab collider, and compare to those at CERN energies. First, we attempt to quantify the SUSY-signal-to-standard-model-background ratios for a range of machine energies. Next, we identify the regions of $m_{\tilde{q}}$ and $m_{\tilde{g}}$ which collider experiments should be able to probe in the first 2 years of Fermilab Tevatron operation. Finally, we indicate salient features of scalar quarks and gluinos in this mass range which may aid in their identification. In particular, we note how the $\not{p}_T$ spectrum scales with the mass of the associated SUSY particles, and we point out the likelihood of SISP's decaying to W gauginos ($\tilde{W}$) and Z gauginos ($\tilde{Z}$) in addition to the decays to photinos ($\tilde{\gamma}$) usually considered. At CERN collider energies, the W- and Z-gaugino decay modes have the effect of reducing the multijet + $\not{p}_T$ cross section typically by at most a factor of 2, but the reduction could be much larger for higher-mass SUSY particles accessible at the Fermilab collider. As a result of the new decay modes, however, there would be additional signals including leptons: events with n jets + m leptons+$\not{p}_T$, where $m=0$–3, and $n=0$–$n_{\max}$, where $n_{\max}$ is the maximum number of jets resolvable by the detector. In this paper, we assume that the photino ($\tilde{\gamma}$) is the lightest SUSY particle and that its lifetime is sufficiently long that it escapes detection.

II. SUSY SIGNAL AND STANDARD-MODEL BACKGROUND

The dominant processes for producing pairs of SISP's in $p\bar{p}$ collisions are the following reactions:

$$q_i\bar{q}_j \to \tilde{q}_i\bar{\tilde{q}}_j\,, \tag{1a}$$

$$q_i q_j \to \tilde{q}_i\tilde{q}_j\,, \tag{1b}$$

$$gg \to \tilde{q}_i\bar{\tilde{q}}_i\,, \tag{1c}$$

$$q\bar{q} \to \tilde{g}\tilde{g}\,, \tag{1d}$$

$$gg \to \tilde{g}\tilde{g}\,, \tag{1e}$$

$$gq \to \tilde{g}\tilde{q}\,. \tag{1f}$$

The gluino is usually assumed to decay mainly via

$$\tilde{g}\rightarrow q\bar{q}\tilde{\gamma},\ m_{\tilde{g}}<m_{\tilde{q}}, \tag{2a}$$

or

$$\tilde{g}\rightarrow\tilde{q}\bar{q},\bar{\tilde{q}}q,\ m_{\tilde{g}}>m_{\tilde{q}}\ . \tag{2b}$$

Scalar quarks have the following dominant decay modes:

$$\tilde{q}\rightarrow q\tilde{\gamma},\ m_{\tilde{q}}<m_{\tilde{g}}; \tag{3a}$$

and

$$\tilde{q}\rightarrow q\tilde{g},\ m_{\tilde{q}}>m_{\tilde{g}}\ . \tag{3b}$$

Decay modes to gauginos ($\tilde{W}$ and $\tilde{Z}$) may also be allowed, and will be discussed later. We ignore production mechanisms involving SISP's in the initial state because they are of negligible importance compared to Eq. (1) for the high-mass SISP's considered in this paper.

The production and decay modes listed in Eqs. (1)—(3) give rise to events in which there are n hadronic jets plus missing transverse momentum (n jets$+\not{p}_T$). The jets arise from materialization of the final-state quarks and gluons, whereas missing p_T is carried away by the $\tilde{\gamma}$'s. The exact n jet $+\not{p}_T$ event topology depends on the experimental cuts implemented, and upon the definition of a "jet." The presence of large $\not{p}_T$ distinguishes the supersymmetry signal from multijet production which proceeds via quantum chromodynamic (QCD) mechanisms.

Many authors have developed event generators to simulate production of SISP's. In the most recent analysis by Barnett, Haber, and Kane the limit $m_{\tilde{g}}>60$—70 GeV ($m_{\tilde{q}}>65$—75 GeV) is obtained, depending on the mass of the $\tilde{q}$ ($\tilde{g}$) (Ref. 5). The plot of the production cross sections versus SUSY-particle mass at $\sqrt{s}=630$ GeV shows a typical decrease in σ_{total} of a factor between 5 and 10 when SUSY-particle masses are increased from 60 to 80 GeV (see, e.g., Figs. 3 and 4). This rapid decrease of cross section indicates that it will be difficult to extend SUSY-particle mass limits much beyond the above values at the CERN $p\bar{p}$ collider, at least until the new antiproton accumulator begins operation. On the other hand, as noted in Ref. 5, two dijet events with $\not{p}_T>55$ GeV in the second data sample[9] of the UA1 collaboration may be consistent with a scalar quark of mass $m_{\tilde{q}}=70$—90 GeV. Moreover, new events with $\not{p}_T>50$ GeV in a third data sample[10] seem to indicate the persistence of the $\not{p}_T$ signal. Supersymmetric particles may be present in the CERN data, but only at the edge of observability.

Various processes within the framework of the standard model yield events with $\not{p}_T$. These backgrounds must be understood and removed from the data sample before a SUSY signal can be claimed. Detailed calculations were performed by Ellis, Kleiss, and Sterling[8] who found a substantial contribution from the following processes:

$$\text{parton-parton}\rightarrow Z+\text{jets, with } Z\rightarrow\nu\bar{\nu}, \tag{4a}$$

$$\text{parton-parton}\rightarrow W+\text{jets, with } W\rightarrow l\nu, \tag{4b}$$

$$\text{or } W\rightarrow\tau\nu\rightarrow l+\not{p}_T \tag{4c}$$

$$\text{or } W\rightarrow\tau\nu\rightarrow h+\not{p}_T\ . \tag{4d}$$

In Eqs. (4), l indicates a charged lepton, e or μ, which has

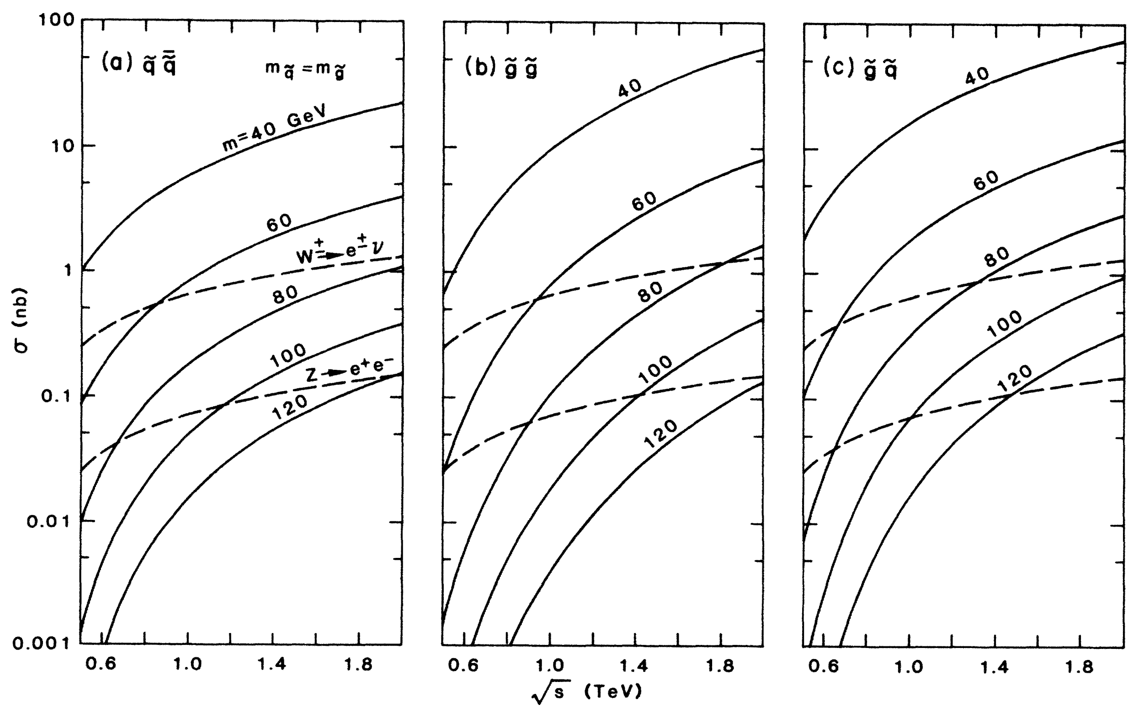

FIG. 1. Total cross sections vs collider energy for various SUSY-particle masses for (a) $\tilde{q}\bar{\tilde{q}}$ and $\tilde{q}\tilde{q}$, (b) $\tilde{g}\tilde{g}$, and (c) $\tilde{g}\tilde{q}$ production. In all cases, $m_{\tilde{q}}=m_{\tilde{g}}$. Also shown is the increase in total cross section for $Z^0\rightarrow e^+e^-$ and $W^{\pm}\rightarrow e\bar{\nu}_e,\bar{e}\nu_e$ (dashed curves).

been "lost" either for instrumental reasons or because it is buried in a hadronic jet. The number n of jets produced is $n \geq 0$, and $\not{p}_T$ arises from final-state neutrinos, lost particles, and measurement errors. Ellis, Kleiss, and and Stirling[8] find that

$$\sigma(E_T^{\text{miss}} > 40 \text{ GeV}) = 10-20 \text{ pb},$$

depending upon the choice of structure functions. These results are not inconsistent with an explanation of the entire observed $\not{p}_T$ sample in terms of standard-model sources.

The first $p\bar{p}$ collisions at the Fermilab Tevatron collider were observed in October 1985, at $\sqrt{s} = 1.6$ TeV, and major data acquisition is expected to begin by the end of 1986. For scalar quarks or gluinos of mass ~ 80 GeV the main effect of an increase in $\sqrt{s}$ is a decrease in the fractional longitudinal momenta of the incoming partons, which in turn results in a higher relative gluon luminosity. For example, in $\bar{p}p$ collisions, at parton-parton center-of-mass energy $\simeq 160$ GeV, the $\bar{u}u$ and gg luminosities grow by factors of ~ 10 and ~ 200, respectively, when $\sqrt{s}$ is increased from 0.54 to 2.0 TeV. Since SISP's are produced in the Born approximation, Eq. (1), via glue-glue and glue-quark fusion as well as by quark-(anti)quark fusion, the large increase of the gluon luminosity should lead to a rapid rise in the SISP cross sections as $\sqrt{s}$ changes from CERN to Fermilab collider energies.

Standard-model sources of $\not{p}_T$ are also fed by qg, gg, qq, and $q\bar{q}$ interactions. In particular, gg and gq subprocess play a role in the production of W's and Z's at large p_T. Nevertheless, the total cross section for the production of these two bosons in $p\bar{p}$ collisions is specified by the Drell-Yan subprocesses, $q\bar{q} \to Z$ and $q\bar{q} \to W$. The energy dependence for production of Z's and W's is therefore characterized by the relatively slow growth with energy of the $q\bar{q}$ luminosity. Since W and Z decays are believed to be the principal standard-model sources of $\not{p}_T$, we expect the standard-model background to grow much less rapidly with energy than the SUSY signal.

In Fig. 1 we plot the total cross sections versus collider energy for a range of SUSY-particle masses, for (a) $\tilde{q}\bar{\tilde{q}}$ and $\tilde{q}\tilde{q}$, (b) $\tilde{g}\tilde{g}$, and (c) $\tilde{g}\tilde{q}$ production. We set $m_{\tilde{q}} = m_{\tilde{g}}$. For a given SUSY-particle mass, the choice of equal masses for the gluino and scalar quark leads to the largest SISP cross sections. This is the case because t-channel gluino and scalar-quark exchange diagrams contribute with full strength and because there are large contributions from the $\tilde{g}\tilde{q}$ channel. We have assumed five degenerate scalar-quark flavors, and $m_{\tilde{q}_L} = m_{\tilde{q}_R}$, and have convoluted the cross-section formulas of Harrison and Llewellyn Smith[3] with the parton distributions of Duke and Owens,[11] with $\Lambda_{\text{QCD}} = 200$ MeV. Also shown in Fig. 1 is the increase in cross sections for W and Z production. As anticipated, the cross sections for producing SISP's rise at a much faster rate than those for producing W's and Z's. In fact, if we assume a 1:1 SUSY signal-to-background ratio at $\sqrt{s} = 0.63$ TeV for a SUSY particle of mass 80 GeV, then we expect this ratio to increase by a factor of 12 when $\sqrt{s}$ is increased from 0.63 to 1.6 TeV.

A different choice of SUSY-particle masses is made in Fig. 2 where we illustrate the extreme cases of (a) $\tilde{q}\bar{\tilde{q}}$ and $\tilde{q}\tilde{q}$ production with $m_{\tilde{g}} = 1$ TeV and (b) $\tilde{g}\tilde{g}$ production with $m_{\tilde{q}} = 1$ TeV. The value 1 TeV is the theoretical upper limit[1] on SUSY-particle masses. In these extreme cases, SISP production cross sections are smallest because only s-channel diagrams contribute and $\tilde{g}\tilde{q}$ production is suppressed. The SUSY signal-to-background enhancement should be about 9.2 and 9.6 in Figs. 2(a) and 2(b), respectively, when $\sqrt{s}$ is varied over the range 0.63—1.6 TeV. With such an enhancement of signal, and signal-to-background ratio, any SISP's lurking at the edge of observability in the CERN collider data should be visible easily in Fermilab collider data.

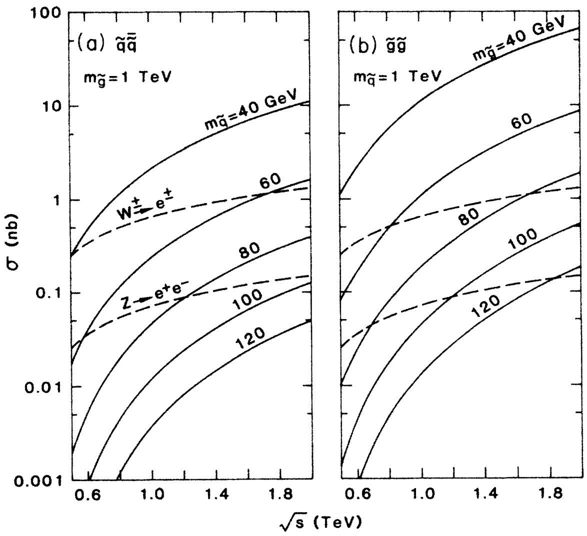

FIG. 2. Total cross sections vs collider energy for (a) $\tilde{q}\bar{\tilde{q}}$ and $\tilde{q}\tilde{q}$ production when $m_{\tilde{g}} = 1$ TeV and (b) $\tilde{g}\tilde{g}$ production when $m_{\tilde{q}} = 1$ TeV.

III. SEARCHING FOR SISP'S AT THE FERMILAB TEVATRON COLLIDER

In this section we attempt to identify the regions of $m_{\tilde{q}}$ and $m_{\tilde{g}}$ which Fermilab collider experiments should be able to probe. The search for scalar quarks and gluinos at Fermilab will be qualitatively different from the search at CERN in several respects: (1) for a SUSY particle of given mass, the smaller fractional longitudinal momenta, x, associated with the incoming partons result in a higher fraction of gluon-initiated events; (2) if the bounds of Barnett, Haber, and Kane[5] are valid, the search region will be substantially higher, i.e., $60 \lesssim m_{\text{SUSY}} \lesssim 150$ GeV, meaning that the expected $\not{p}_T$ spectrum will be harder, and backgrounds from standard-model sources of less consequence; (3) if $N=1$ supergravity models are used as a guide, it is likely that scalar-quark and gluino decays to W and Z gauginos will become important,[12] and it will no longer be sufficient to restrict one's analysis to the case of SISP's decaying to photinos.

We begin our discussion by showing expected topological jet cross sections as a function of mass of the SISP's. Subsequently we examine transverse-momentum distributions, and we end this section with a treatment of SISP decays into W and Z gauginos, $\tilde{W}$ and $\tilde{Z}$.

A. Topological jet cross sections

As indicated in Eqs. (2) and (3), a gluino decays into two partons plus missing energy, whereas a scalar quark decays into either one or three partons plus missing energy. The partons materialize as hadronic jets. Whether one, two, or more hadronic jets will be resolved in a given event depends upon the capabilities of one's detector and the definition adopted for a jet. Since the principal signature of a supersymmetry candidate is the presence of missing p_T, we compute topological jet cross sections for a specified selection on $\not{p}_T$.

We adopt the following cuts inspired by those used by the CERN UA1 Collaboration carrying them over to the Fermilab case as a rough approximation. First we order final-state partons according to their transverse energies E_T, and then coalesce partons lying within

$$\Delta r = (\Delta\eta^2 + \Delta\phi^2)^{1/2} < 1 \ . \quad (5)$$

As usual η and ϕ are rapidity and azimuthal angle variables. We then require

$$\not{p}_T > \mathrm{Max}(15\ \mathrm{GeV}, 4\sigma) ,$$
$$\sigma = 0.7\ \mathrm{GeV}^{1/2} \left[\sum_{\text{partons}} E_T + 20\ \mathrm{GeV} \right]^{1/2} . \quad (6)$$

We restrict jet transverse momenta and rapidities such that

$$|p_{T_{j1}}| > 25\ \mathrm{GeV}, \quad |p_{T_{j2}}| \geq 12\ \mathrm{GeV}, \quad |\eta_j| < 2.5 \ . \quad (7)$$

In implementing these cuts, we are not trying to simulate in detail any specific detector; we are concerned mainly with the overall qualitative behavior of the supersymmetric events.

Our principal intent here is to define the range of masses of the scalar quark and gluino which may be explored by Fermilab collider experiments. Correspondingly, we set $m_{\tilde{g}} \to \infty$ which, as explained above, minimizes the predicted cross section for $\tilde{q}$ production. In Fig. 3 we show the expected topological cross sections for $\tilde{q}\bar{\tilde{q}}$ and $\tilde{q}\tilde{q}$ production versus $m_{\tilde{q}}$ at (a) 0.63 TeV and (b) 1.6 TeV. The $\tilde{g}\tilde{g}$ case with $m_{\tilde{q}} = \infty$ is illustrated in Fig. 4.

The limits derived by Barnett, Haber, and Kane,[5] $m_{\tilde{q}} \gtrsim 65$–75 GeV and $m_{\tilde{g}} \gtrsim 60$–70 GeV, for $\sqrt{s} = 630$ GeV were based on a data sample with 270 nb^{-1} of integrated luminosity. This figure is comparable to the 400 nb^{-1} which it is hoped will be accumulated during the first 2 years of operation of the Fermilab collider.[13] Assuming then that Fermilab collider experiments will be sensitive to the same cross sections as the UA1 experiment at CERN, we can use Figs. 3 and 4 to extrapolate the lower bounds of Barnett, Haber, and Kane, from CERN to Fermilab collider energies. We find that during the first 2 years of operation, Fermilab collider experiments should be sensitive to at least $m_{\tilde{q}} = 120$ GeV and $m_{\tilde{g}} = 150$ GeV (when $m_{\tilde{g}} = \infty$ and $m_{\tilde{q}} = \infty$, respectively). These are conservative lower bounds. As explained earlier, more realistic choices for SISP masses will result in larger cross sections than the lower limits shown in Figs. 3 and 4.

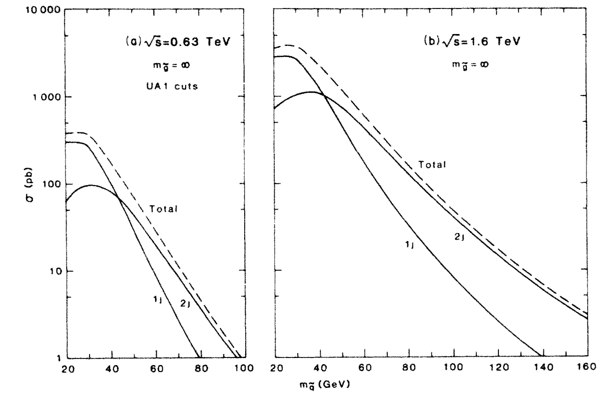

FIG. 3. Topological-cross-section estimates vs scalar-quark mass for $\tilde{q}\bar{\tilde{q}}$ and $\tilde{q}\tilde{q}$ production when $m_{\tilde{g}} = \infty$ for (a) $\sqrt{s} = 0.63$ TeV and (b) $\sqrt{s} = 1.6$ TeV. Both plots incorporate the cuts described in the text.

For the particular choices of SISP masses made in Figs. 3 and 4, we note that the topological signatures are very similar at 0.63 and 1.6 TeV. The major effect of the increase in $\sqrt{s}$ is to increase the magnitude of various topological cross sections. The SUSY-particle mass at which the n jet and $n+1$ jet cross sections become equal remain nearly the same. The event topology is governed mainly by two factors: the SUSY-particle mass and the SUSY-particle transverse momentum. For SUSY-particle masses in the range of interest at the Tevatron, the ratio of the dijet to monojet yields in Figs. 3 and 4 exceeds unity and grows monotonically with the SUSY-particle masses. In Fig. 4, with the jet definitions we have adopted, we note that the ratio of the trijet to monojet cross sections also exceeds unity for gluino masses greater than 50 GeV and rises rapidly thereafter.

B. Transverse-momentum distributions

It is an interesting result of our Monte Carlo calculations that the mean transverse momentum of SUSY particles ($\langle p_T \rangle$) changes little with increasing collider energy. In fact, for $m_{\tilde{q}} = 80$ GeV ($m_{\tilde{g}} = \infty$), we find $\langle p_{T_{\tilde{q}}} \rangle = 55$ GeV at $\sqrt{s} = 0.63$ TeV, and $\langle p_{T_{\tilde{q}}} \rangle = 53$ GeV at $\sqrt{s} = 1.6$ TeV—a slight decrease in mean p_T. This can be understood by noting that for $\tilde{q}\bar{\tilde{q}}$ production at 0.63 TeV ($m_{\tilde{q}} = 80$ GeV), 20% of the cross section comes from glue-glue fusion with $\langle p_{T_{\tilde{q}}} \rangle = 30$ GeV, and 80% comes from the $q\bar{q}$ fusion with $\langle p_{T_{\tilde{q}}} \rangle = 61$ GeV. In the 1.6-TeV case, we find 70% of the cross section is from glue-glue

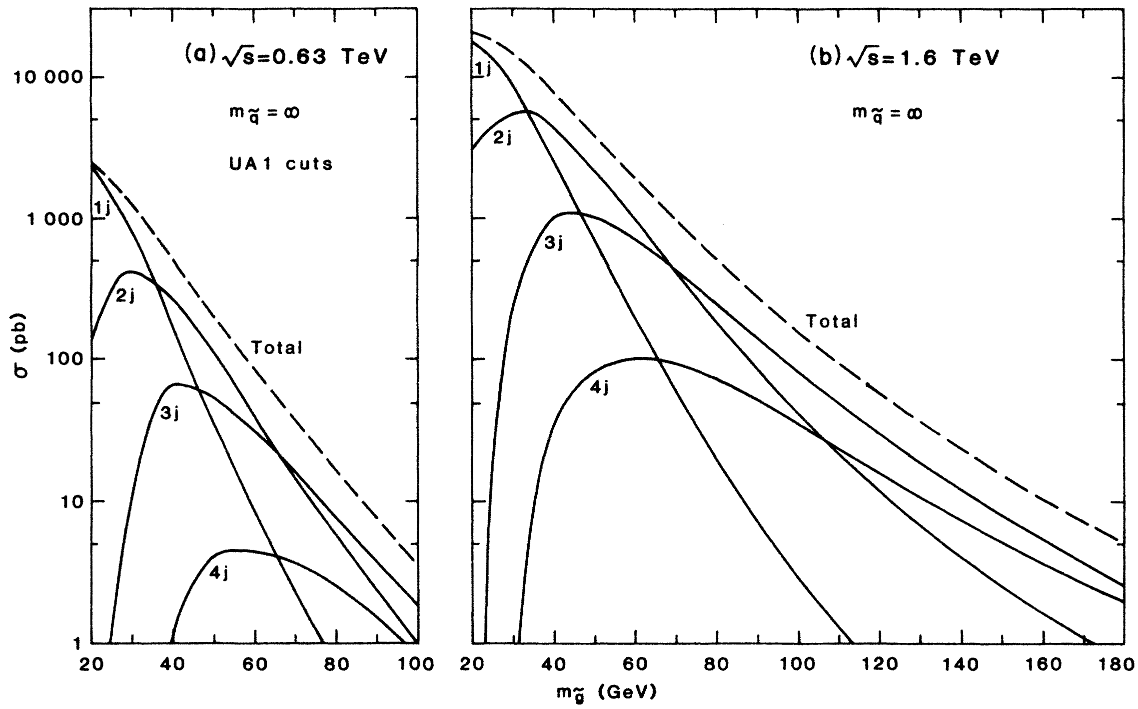

FIG. 4. Topological cross sections vs gluino mass for $\tilde g\tilde g$ production when $m_{\tilde q}=\infty$ for (a) $\sqrt{s}=0.63$ TeV and (b) $\sqrt{s}=1.6$ TeV. The cuts for both plots are the same as in Fig. 3.

fusion with $\langle p_{T_{\tilde q}}\rangle=40$ GeV, while the other 30% is from $q\bar q$ and has $\langle p_{T_{\tilde q}}\rangle=82$ GeV. Results are similar for $\tilde g\tilde g$ production with $m_{\tilde q}=\infty$. For $m_{\tilde q}=80$ GeV, we find $\langle p_{T_{\tilde g}}\rangle=75$ GeV at $\sqrt{s}=0.63$ TeV, and $\langle p_{T_{\tilde g}}\rangle=78$ GeV at $\sqrt{s}=1.6$ TeV. These differences in the mean transverse momentum are due to the fact that angular distributions are different[14] for SUSY particles produced by gg or $q\bar q$ fusion.

In Fig. 5, we plot the expected $\not p_T$ spectrum from all multijet $+\not p_T$ events, using the UA1 cuts. These results, normalized to unit cross section, are virtually independent of beam energy for the range considered: $0.6<\sqrt{s}<2$ TeV. The SUSY-particle mass region of most interest at the Tevatron collider, $60\lesssim m\lesssim 150$ GeV, is characterized by very hard $\not p_T$ distributions. In the $\tilde q\tilde q$ case, events are distributed over a broad range of $\not p_T$ between the minimum $\not p_T$ cutoff $\not p_{T_0}$ and the scalar-quark mass, so we have, roughly

$$\langle \not p_T\rangle \sim \frac{m_{\tilde q}+\not p_{T_0}}{2} . \tag{8}$$

For comparable SUSY-particle masses, the $\tilde g\tilde g$ $\not p_T$ spectrum is softer, as shown in Fig. 5(b). In this case, the mean $\not p_T$ is roughly

$$\langle \not p_T\rangle \sim \frac{m_{\tilde g}}{2} , \tag{9}$$

and the distributions are in general narrower than in the scalar-quark case. Standard-model backgrounds from vector-boson production[8] drop off sharply with $\not p_T$. They should be of less consequence for the higher-mass SUSY particles accessible at the Fermilab collider than they are at CERN energies.

C. Decays to W and Z gauginos

In all of our analysis thus far, we have assumed that SISP's decay into photinos, as shown in Eq. (2), with 100% branching fractions. In the simplest $N=1$ supergravity models, masses of scalar fermions (scalar quarks and scalar leptons) are expected to be ~ 100 GeV, while

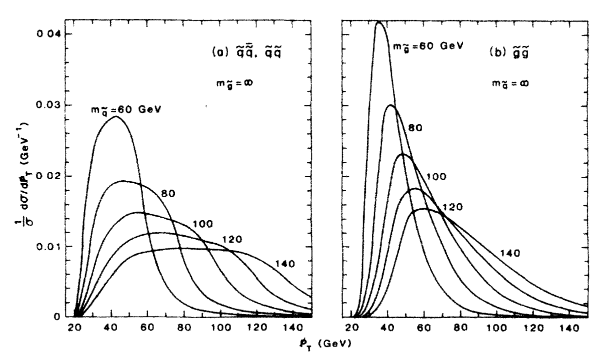

FIG. 5. Distribution in missing $p_T(\not p_T)$ for the two extreme cases of (a) $\tilde q\bar{\tilde q}$ and $\tilde q\tilde q$ production with $m_{\tilde g}=\infty$ and (b) $\tilde g\tilde g$ production with $m_{\tilde q}=\infty$. The area under the curves is normalized to unity; the results are insensitive to collider energy between 0.5 and 2 TeV.

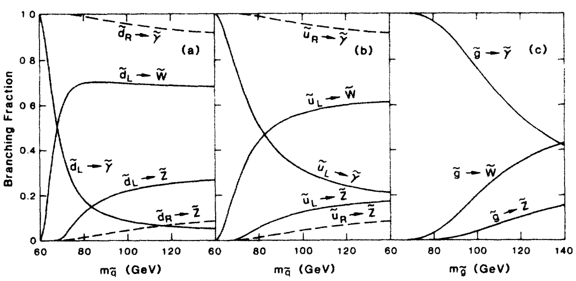

FIG. 6. Branching fraction to gauginos ($\tilde{\gamma},\tilde{W},\tilde{Z}$) vs SUSY-particle mass for $m_{\tilde{\gamma}}=8$ GeV, $m_{\tilde{W}}=60$ GeV, and $m_{\tilde{Z}}=68$ GeV, for left- and right-handed (a) down-type scalar quarks, (b) up-type scalar quarks, and for (c) gluinos.

those of the light gauginos $\tilde{W}$ and $\tilde{Z}$ are expected to be less than the masses of the associated vector bosons (when the photino is light).[15] In addition to the decays of Eq. (2), we would then expect

$$\tilde{q}_L \to q\tilde{W}\,, \tag{10a}$$

$$\tilde{q}_{L,R} \to q\tilde{Z}\,, \tag{10b}$$

and

$$\tilde{g} \to q\bar{q}\tilde{W}\,, \tag{10c}$$

$$\tilde{g} \to q\bar{q}\tilde{Z}\,. \tag{10d}$$

The branching fractions to W gauginos can frequently be large.

In Fig. 6 we plot the branching fractions of (a) down-type scalar quarks, (b) up-type scalar quarks, and (c) gluinos into gauginos as a function of SISP mass. We set the W-gaugino mass, $m_{\tilde{W}}=60$ GeV, and Z-gaugino mass, $m_{\tilde{Z}}=68$ GeV; these choices are motivated by the theoretical arguments mentioned above and by possible lower bounds[16] from CERN collider data. The couplings of Ref. 12 are used. The branching fraction for $\tilde{u}_R(\tilde{d}_R) \to \tilde{Z}+u(d)$ is very small, approaching 12% as $m_{\tilde{q}} \to \infty$, and the decay $\tilde{u}_R(\tilde{d}_R) \to \tilde{W}+d(u)$ does not exist. However, the branching fractions for $\tilde{u}_L(\tilde{d}_L) \to \tilde{Z}+u(d)$ can be as large as 24% (32%) for large scalar-quark masses, while those for $\tilde{u}_L(\tilde{d}_L) \to \tilde{W}+d(u)$ can be even larger, approaching 63% (64%). As shown in Fig. 6(c), the gluino branching fractions to gauginos are also large when $m_{\tilde{g}} > m_{\tilde{Z}}, m_{\tilde{W}}$. As $m_{\tilde{g}}$ approaches infinity, the branching fractions for $\tilde{g} \to \tilde{\gamma}$, $\tilde{W}$, $\tilde{Z}$ are 0.15, 0.55, and 0.30, respectively. The usual assumption, made in Ref. 3, of 100% branching fractions for SISP decays to photinos may not be reasonable for scalar quarks and gluinos whose mass is greater than $m_{\tilde{W}}$. In the paragraphs to follow we examine the effects of SISP decays to gauginos for the separate cases of $\tilde{q}\bar{\tilde{q}}$, $\tilde{g}\tilde{g}$, and $\tilde{g}\tilde{q}$ production.

1. $\tilde{q}\bar{\tilde{q}}$ and $\tilde{q}\tilde{q}$ production

If $m_{\tilde{g}}=\infty$, scalar quarks are produced in the ratio

$$\tilde{q}_L\bar{\tilde{q}}_L : \tilde{q}_R\bar{\tilde{q}}_R : \tilde{q}_L\bar{\tilde{q}}_R + \tilde{q}_R\bar{\tilde{q}}_L = 1{:}1{:}0\,.$$

As $m_{\tilde{g}}$ is decreased to a more realistic value, t-channel graphs begin to contribute to the total cross section, and events containing both left-handed and right-handed scalar quarks become more numerous. They can even dominate the scalar-quark pair cross section at CERN energies when $m_{\tilde{g}}$ is light enough ($\approx m_{\tilde{q}}$) (Ref. 14). Calculations of scalar-quark pair production ($m_{\tilde{q}}<60$ GeV) with scalar-quark decays to gauginos have been performed for the CERN collider.[12] It was found that typically the n jet$+\not{p}_T$ cross section was reduced by at most a factor of 2 for the range of scalar-quark masses accessible to experimental detection at CERN. In addition, there can exist n jet$+m$ lepton$+\not{p}_T$ signals at an observable level. The reduction by at most a factor of 2 arises in part because left- and right-handed scalar quarks are produced in equal numbers and the decay of right-handed scalar quarks remain predominantly to photinos. For $m_{\tilde{q}}<120$ GeV at $\sqrt{s}=1.6$ TeV, scalar-quark pairs are produced primarily by gg fusion. Hence pairs of left-handed and pairs of right-handed scalar quarks will be produced in equal numbers, and few left-right pairs will occur. Since the right-handed scalar quarks decay principally to photinos, as shown in Figs. 6(a) and 6(b), we expect the CERN collider results mentioned above to remain valid for the more massive scalar quarks accessible at Fermilab.

2. $\tilde{g}\tilde{g}$ production

Detailed calculations have not been published for gluino pair production including decays to gauginos. If $m_{\tilde{g}}>m_{\tilde{q}}$, the gluino would decay according to Eq. (2b) into a quark—scalar-quark system. The scalar quark is equally likely to be right or left handed. Ultimately, decays to photinos would account for more than 50% of the gluino decay rate. On the other hand, if $m_{\tilde{W},\tilde{Z}}<m_{\tilde{g}}<m_{\tilde{q}}$, we must consider

$$\tilde{g} \to q\bar{Q}\tilde{W},\quad \tilde{W} \to Q'\bar{q}'\tilde{\gamma} \ \text{ or } l\nu\tilde{\gamma} \tag{11a}$$

and

$$\tilde{g} \to q\bar{q}\tilde{Z},\quad \tilde{Z} \to q\bar{q}\tilde{\gamma} \ \text{ or } l\bar{l}\tilde{\gamma}\,. \tag{11b}$$

As a result of these competing decay modes, the branching fraction for gluinos to photinos could be as small as 15%. The reduction arises because the couplings of $\tilde{W}$'s and $\tilde{Z}$'s to $\tilde{q}_L$ are much larger than those to $\tilde{q}_R$. This effect can result in gluino decay through a virtual $\tilde{q}_L$, 10 times as frequently as through a virtual $\tilde{q}_R(m_{\tilde{q}_L}=m_{\tilde{q}_R})$. Alterations to include these decays will have to be made in the Monte Carlo simulation programs of many of the papers of Ref. 3 if the authors wish to apply their calculations to Fermilab collider energies. If the decays shown in Eqs. (11) are allowed, the $\not{p}_T$ spectrum will be considerably softened, and $\tilde{g}\tilde{g}$ events will be more difficult to distinguish from standard-model background processes.

3. $\tilde{g}\tilde{q}$ production

If $m_{\tilde{g}}>m_{\tilde{q}}$, the $\tilde{g}$ from the $\tilde{q}\tilde{g}$ final state will decay according to Eq. (2b): $\tilde{g} \to q\bar{\tilde{q}}$ or $\bar{q}\tilde{q}$. The final-state scalar quarks will occur in the ratio

$$\tilde{q}_L\tilde{q}_L : \tilde{q}_R\tilde{q}_R : \tilde{q}_L\tilde{q}_R = 1{:}1{:}2\,.$$

At least 25% of the cross section will be associated with a hard $\not{p}_T$ spectrum. However, if $m_{\tilde{g}}<m_{\tilde{q}}$, gluinos will de-

cay through virtual scalar quarks, and the branching fractions shown in Fig. 6(c) will apply. As little as 8% of the cross section may exhibit the hard $\not{p}_T$ spectrum characteristic of direct decays of SISP's to photinos.

IV. CONCLUSION

We have performed a comparative study of scalar-quark and gluino production at the CERN S$p\bar{p}$S and Fermilab Tevatron $p\bar{p}$ colliders. For a broad range of interesting scalar-quark and gluino masses, cross sections are expected to rise rapidly with energy as $\sqrt{s}$ is changed from 0.63 to 2 TeV. Moreover, the rate of growth of supersymmetric sources of $\not{p}_T$ is much greater than that of standard-model (background) sources associated with W and Z production. If the events observed by the UA1 Collaboration with $\not{p}_T > 50$ GeV are indeed due to SUSY particles near CERN's limit of observability, then Fermilab collider experiments should be able to confirm this signal easily. If SUSY particles have higher masses, the first 400 nb^{-1} of data at the Fermilab collider should provide evidence of their signals up to at least $m_{\tilde{q}} \approx 120$ GeV and $m_{\tilde{g}} \approx 150$ GeV. If decays to photinos are dominant, as is usually assumed, the higher mass SISP's accessible at the Tevatron will be characterized by a very hard $\not{p}_T$ spectrum, and thus there should be less confusion between signal and background processes. However, if decays into W and Z gauginos are allowed along with photinos, then a fraction of the cross section will have a softer $\not{p}_T$ spectrum and may then be hard to distinguish from background. In this case, it is possible to have an observable signal including leptons: events with n jets $+\, m$ leptons $+\, \not{p}_T$.

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