DETECTING SUPERSYMMETRIC HADRONS

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Supersymmetric grand unified models are of interest because they offer a possible explanation of the great disparity between the W mass and the grand unified scale (about 10^{15} GeV). In such models each of the familiar particles (gluons, quarks, etc.) has a partner differing by 1/2 unit of spin, presumably with a mass of order the W mass or less. Supersymmetry ensures that the couplings of the partners of the gluons and quarks to normal hadronic constituents are of about the usual QCD strength. Thus production cross-sections for these states need not be particularly small. In the present paper we investigate the possibility of detecting the sypersymmetric partners of gluons and quarks at a 400 × 400 GeV/c proton-proton collider.

The spin $\frac{1}{2}$ partner of the gluon, the gluino, should decay either into a photino plus a quark-antiquark pair or into a Goldstino plus a gluon. Both the photino and the Goldstino are essentially noninteracting, so the signature is unbalanced P_T plus missing momentum out of the plane. In addition, unlike the gluinos, the potential backgrounds, such as decays of heavy quarks involving neutrinos, tend to produce a lepton of at least moderate P_T.

The detector envisioned is a fine grained Uranium calorimeter covering the kinematic range $-2 < y < 2$, $0 < \phi < 2\pi$. A somewhat coarser grained end cap calorimeter serves to veto events which deposit > 10% of their transverse energy in the region $2 < |y| < 3$. The energy resolution assumed for the U calorimeter is $\sigma_E = .15E^{1/2}$ for electromagnetic and $.35E^{1/2}$ for hadronic particles. Muons are assumed to deposit a maximum of 1.1 GeV/c in the calorimeter.

A modified version of ISAJET[1] was used to produce gluinos in the reaction $pp \to \tilde{g}\tilde{g} + X$ at $\sqrt{s} = 800$ GeV/c according to cross sections provided by G. Kane and J.P. Leveille[2]. Events were generated for $\tilde{g}$ masses of 30 to 125 GeV/c^2. The response of the detector was simulated by smearing the energy of the final state particles with $|y| < 3$ according to the above mentioned resolutions. The sum of the transverse energy for particles with $2 < |y| < 3$ was separately calculated and events where this sum exceeded 10% of the total transverse energy were rejected. A sphericity tensor was calculated for the remaining events. The eigenvector with the largest eigenvalue was considered to be the reference axis. The detectable particles were divided into two groups depending on which hemisphere they lay in with respect to the reference axis. The sum of the transverse momenta of the particles in the hemisphere of the reference axis, $|\vec{P}_T|$, was required to be greater than 20 GeV/c, while the sum in the opposite hemisphere, $|\vec{P}_T'|$, was required to be greater than 5 GeV/c. As measures of the transverse momentum imbalance, the quantities X_E and P_{out} were defined as follows:

$$X_E = \frac{-\vec{P}_T \cdot \vec{P}_T'}{|\vec{P}_T|^2} \text{ and } P_{out} = \sqrt{|\vec{P}_T'|^2 - X_E|\vec{P}_T|^2}$$

Figures 1 and 2 show these distributions for gluino mass 30 GeV/c and 75 GeV/c, where it has been assumed that the gluino undergoes a three body decay ($\tilde{g} \to \tilde{\gamma}q\bar{q}$).[3] Also shown are the corresponding distributions for background events due to QCD production of high P_T light constituents (g, u, d, s). The differences between the distributions of the gluino signal and those of light constituent background are already quite striking at $M_{\tilde{g}} = 30$ and become even more dramatic as $M_{\tilde{g}}$ increases. Thus cuts on these quantitites can be made extremely effective. That such rejection

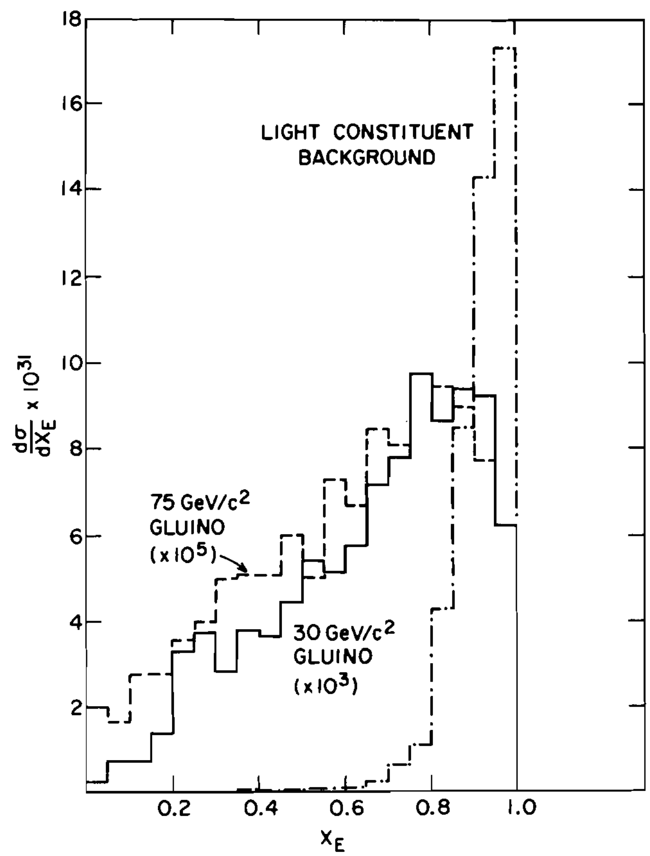

Figure 1. X_E distributions for gluinos of mass 30 and for light constituent background.

is necessary can be seen in Fig. 3, which shows the cross-section vs P_T of 30 GeV/c mass gluinos[4] compared to that of the light constituent background. It is clear that a relative rejection factor of order 500:1 is required.[5] In fact relative rejection rates of ∿ 2000:1 can readily be obtained with cuts which retain ≳ 10% of the gluino signal. One such cut set is $X_E < .5$, $P_{out} > 5$ GeV/c. The resulting detected gluino event rate[3] vs mass is shown in Fig. 4. A total integrated luminosity of $10^{39}/\text{cm}^2$ is assumed. Also shown is the event rate in the case that the P_{out} cut is increased to $P_{out} > 10$ GeV/c. If one regards ∿ 1000 events as the minimum detectable signal for such a process, masses of about 125 GeV/c^2 can be reached. However, in practice this limit may be severely reduced by the presence of background.

To study this question in detail, three types of background processes were simulated by ISAJET, submitted to the same detector emulation program and subjected to the same cuts as the gluino signal.[6] These were:

1) Light constituents (g, u, $\bar{u}$, d, $\bar{d}$, s, $\bar{s}$) scattered to large P_T in hard collisions.

2) $t\bar{t}$ pair production. M_t was assumed to be 20 GeV/c^2.

3) An appropriate mixture of $b\bar{b}$ and $c\bar{c}$ pairs.

The residual backgrounds are shown in Fig. 5. The light constituent background is still the largest, even

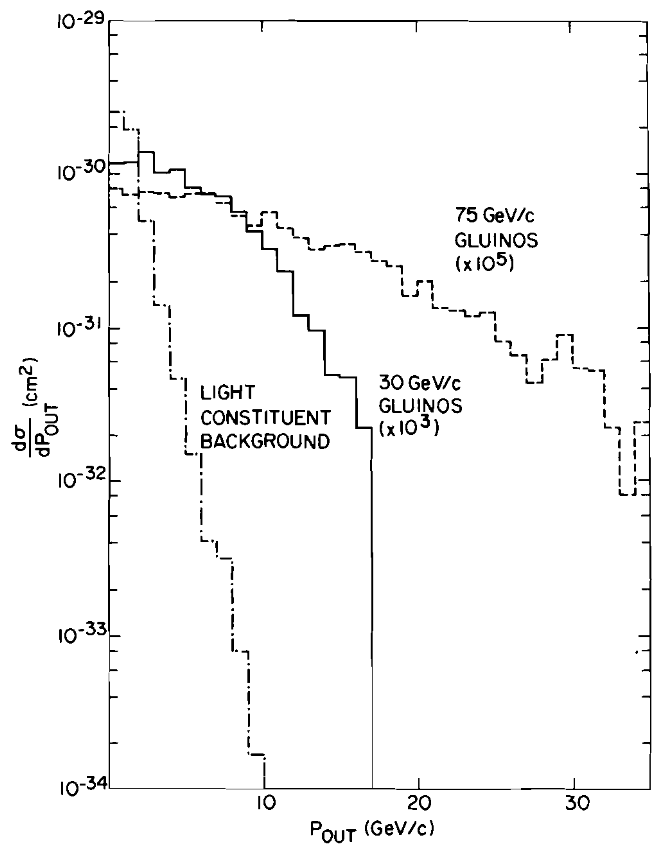

Figure 2. P_{out} distributions for gluinos of mass 30 and 75 GeV/c, and for light constituent background.

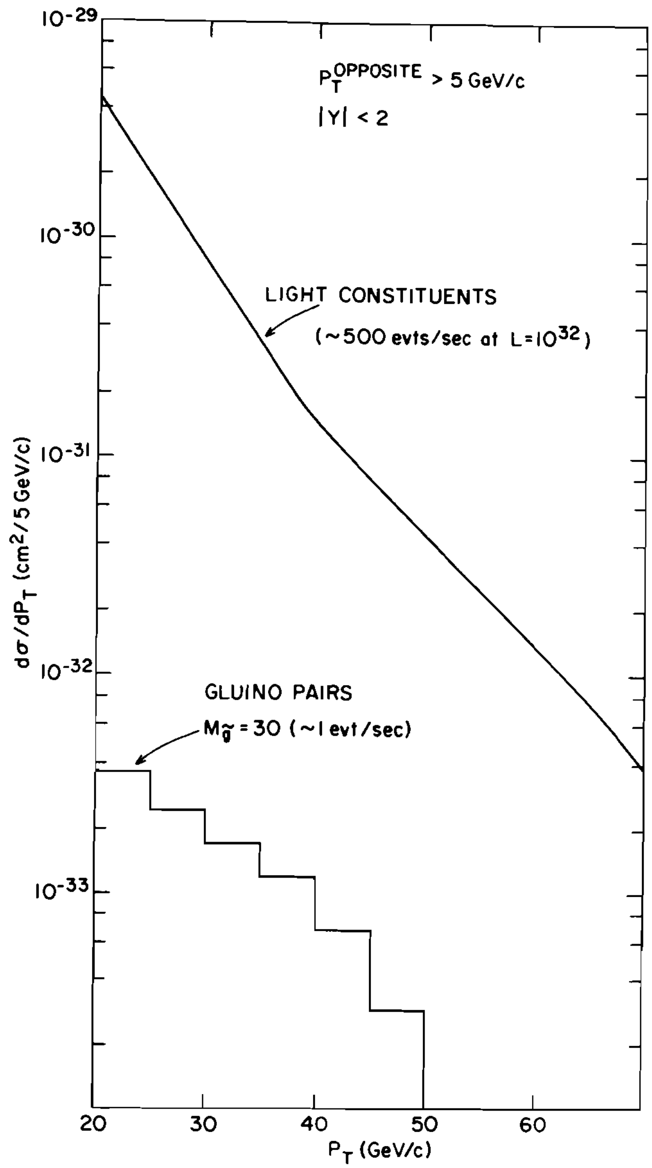

Figure 3. Cross-sections vs P_T for the production of 30 GeV/c gluinos and of light constitutents.

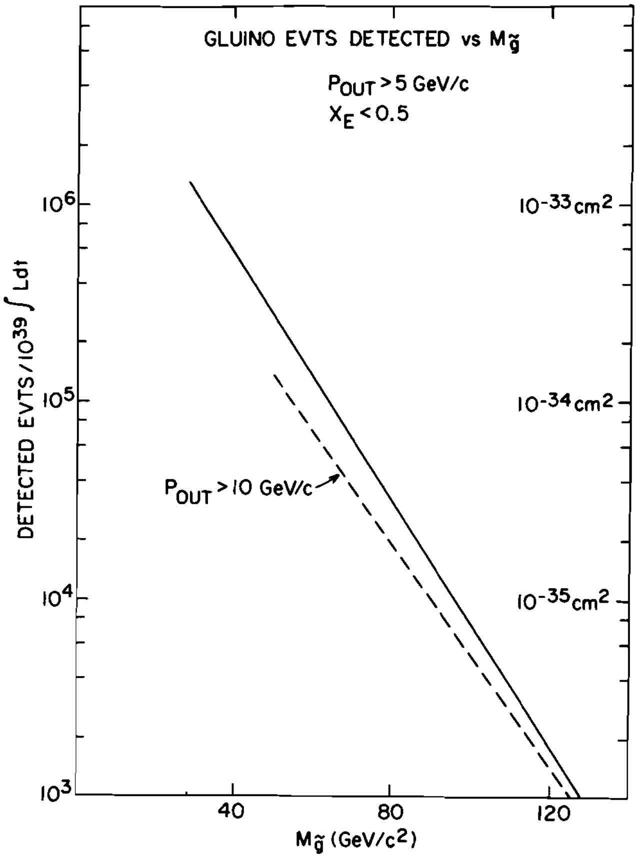

Figure 4. Number of detected gluino events vs mass for an integrated luminosity of 10^{39} cm^{-2}. Upper curve assumes $X_E < .5$, $P_{out} > 5$ GeV/c, lower curve assumes $X_E < .5$, $P_{out} > 10$ GeV/c.

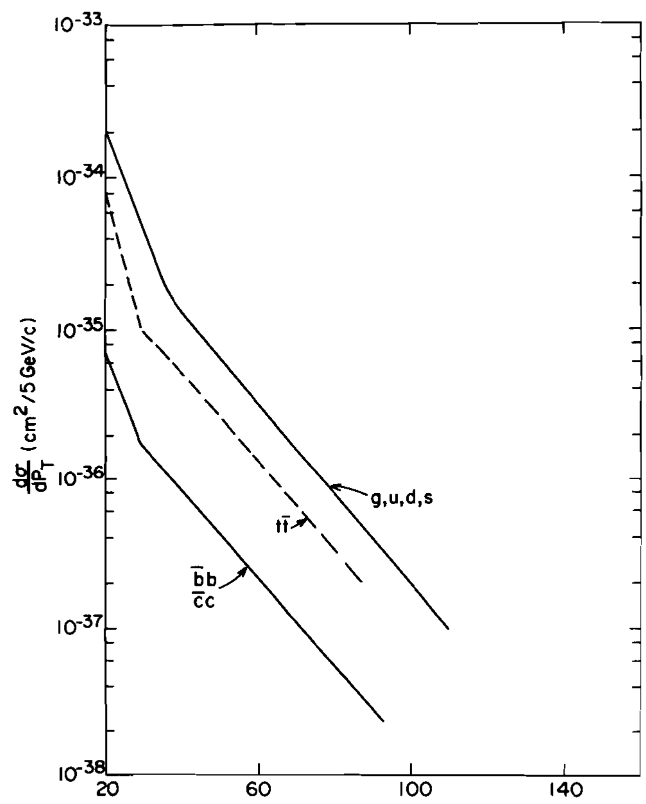

Figure 5. Residual backgrounds after the cuts $X_E < .5$, $P_{out} > 5$ GeV/c have been imposed.

though it has been reduced by a factor of $\sim$ 18000. The $t\bar{t}$ pair production is roughly a factor of three less. The $\bar{b}b$ and $\bar{c}c$ background is down by a further order of magnitude and is thus negligible compared to the other two.

An event by event study of the residual light constituent background yielded a surprising result. It was originally expected on the basis of a previous similar study at lower energy[7] that this process would contribute to the background via the emission of a hard gluon with rapidity sufficient to partially elude the detector thus simulating the gluino kinematics. Instead, it was found that the surviving events all contained high P_T gluons which fragmented into a high mass $\bar{b}b$ or $\bar{c}c$ pair, one member of which subsequently decayed semileptonically. The $\vec{P}_T$ carried off by the neutrino was thus of the order of the gluon $P_T/6$ rather than of $M_b/3$ or $M_c/3$ as in the case of background (3). This has the (useful) consequence that a very large fraction of the residual background contains leptons of substantial energy, which by and large is not true of the gluino events. Lepton identification would thus be extremely desirable. Not only could a large fraction of the background be vetoed, but once the detector was well understood, the measurement of the identifiable lepton events would allow a very good estimation of the residual background (in which the leptons were missed) to be made.

Figure 6 indicates the possibility of extracting the gluino signal from the background. The detected cross-section vs P_T is given for gluinos of mass 30, 50, 75, 100, and 125 GeV/c^2, as is the sum of the background. The signal remains higher than the background, at least for some range of P_T, out to about $M_{\tilde{g}} = 70$ GeV/c. At 75 GeV/c^2 for $P_T > 50$, there are still $\sim$ 16000 gluino pairs to $\sim$ 27500 background events.

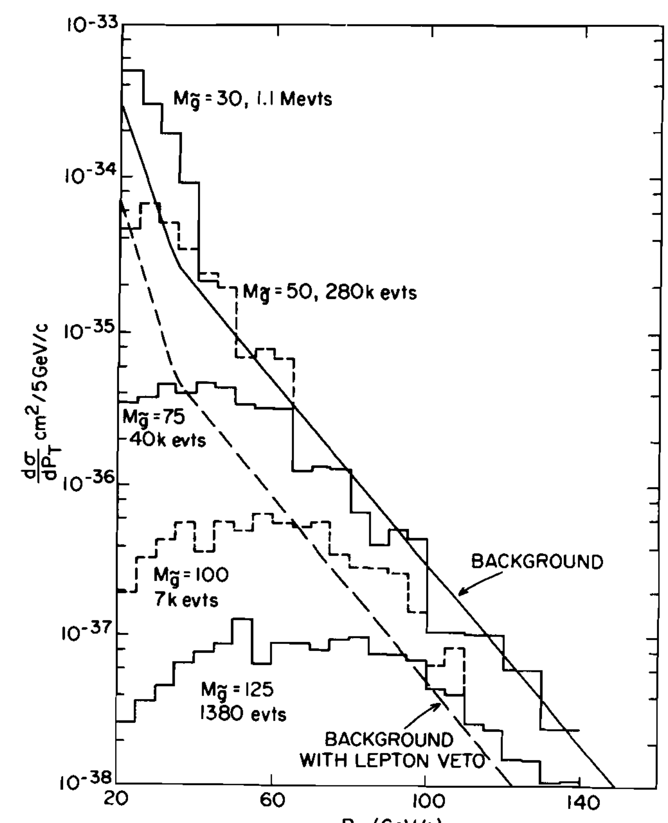

Figure 6. Gluino cross-section vs P_T for $M_{\tilde{g}}$ = 30, 50, 75, 100 and 125 GeV/c^2. Also shown is the combined residual background, and the background remaining after $E_{LEPT} > 2$ GeV cut is made.

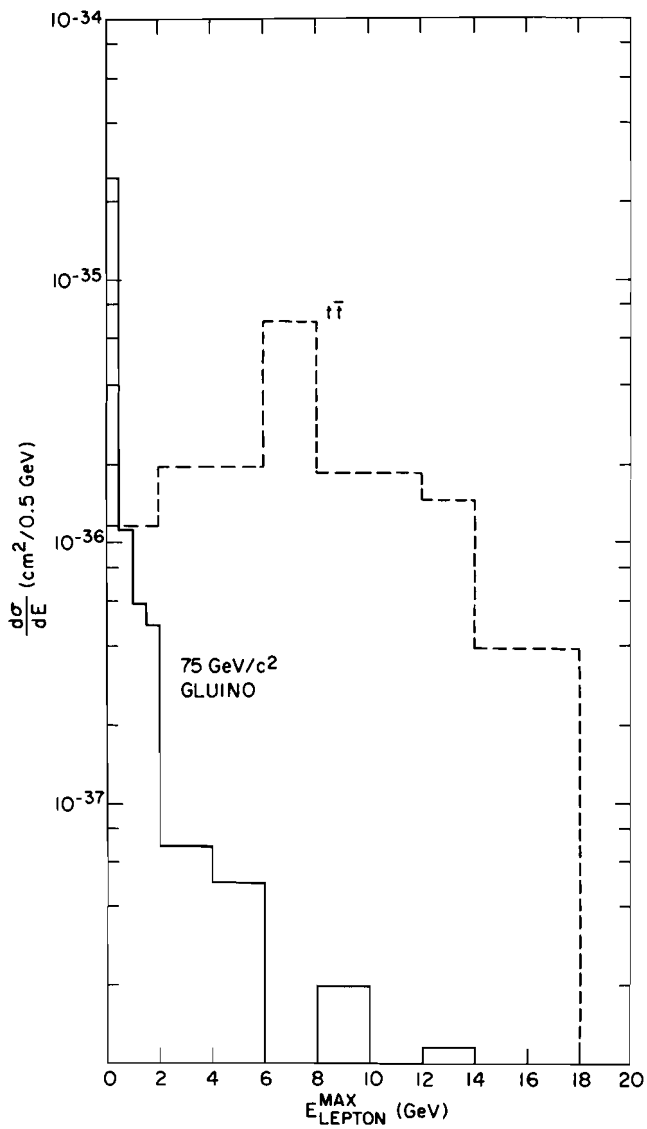

Figure 7. a) Histogram of the maximum lepton energy in each 75 GeV/c gluino event passing $X_E < .5$, $P_{out} > 5$. b) Corresponding distribution for $t\bar{t}$ events.

This represents a signal that can surely be extracted once the backgrounds are thoroughly understood. In addition there are kinematic and other pecularities of the signal events, such as the tendency of the less energetic gluino jet to give a peak in $|\vec{P}_T'|$, which we have not exploited in our study but which could possibly be used to further improve the signal/background. Above $\sim$ 75 GeV/c simply tightening the P_{out} cut to $P_{out} > 10$ GeV/c improves the signal to background by about a factor 2. However, it is clear that much above this mass the signal cannot be extracted without vetoing on leptons. Figure 7 is a histogram of the maximum lepton energy in each detected $M_{\tilde{g}} = 75$ GeV/c^2 gluino event. Also shown is the corresponding distribution for $\bar{t}t$ background events. It is clear that a cut of $\sim$ 2 GeV, leaves the gluino population almost intact while decimating the $t\bar{t}$ events. The corresponding reduction for the light constituent background events is somewhat less, on the order of 4:1. This reduction allows us to detect gluinos up to at least 100 GeV/c^2 where imposing an $E_{LEPT} < 2$ GeV cut, one can obtain $\sim$ 2500 signal and $\sim$ 1250 background events above $P_T = 65$ GeV/c.

Thus, to summarize, at a 400 × 400 GeV/c pp collider, operating at $L \sim 10^{32}/\text{cm}^2$ one can detect a gluino signal via its kinematic signature up to $\sim$ 75 GeV/c or somewhat beyond 100 GeV/c with the use of a lepton veto.

We have also briefly investigated the question of detecting scalar quarks. Unlike the case of gluino pair production which is $\sim$ 5-10 times more copious than the QCD production of heavy quarks for the same mass, scalar quarks are pair produced $\sim$ 5 times less often than ordinary heavy quarks. What is more, since they decay through the chain

$$\phi_q \to \tilde{g} + q, \quad \tilde{g} \to \tilde{\gamma} q\bar{q} \text{ or } \tilde{G}g,$$

the share of the $\vec{P}_T$ ultimately removed by noninteracting particles is less than in the gluino case. This makes the kinematic distributions somewhat less distinct from those of the background. For $M_{\phi_u} = 50$ the resulting, rather discouraging, signal/background ratio is shown in Fig. 8. Here, even with a lepton cut, one has a signal of only 5500 events compared with a background of $\sim$ 70000.

Thus detecting scalar quarks produced in pairs appears hopeless in the mass region of most interest ($M \sim M_W$). However, in the course of this study it was observed that the leading diagrams for ϕ_q production will be those of Fig. 9. This process in fact produces several hundred times more ϕ_q's than does pair production.[8] Figure 10 shows the detected cross-section vs P_T for a 30 GeV gluino + a 50 GeV/c scalar quark produced in this manner. The background shown for comparision has not been subjected to a lepton cut. Even so, there is clearly no difficulty in extracting a signal. Further details on the use of this process to produce and detect supersymmetric particles await a future publication.

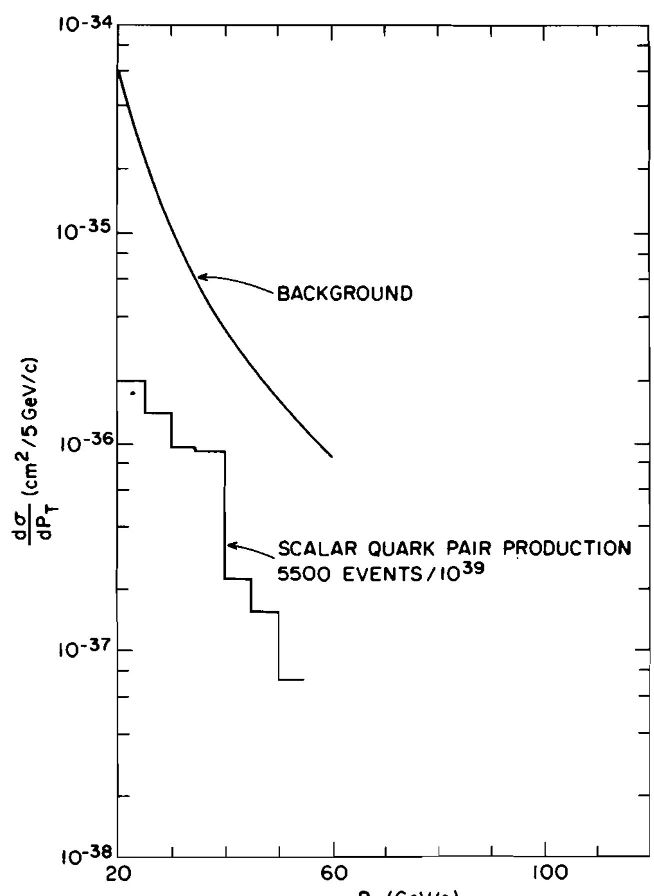

Figure 8. Scalar u-quark pair production cross-section vs P_T for $M_{\phi_u} = 50$, $M_{\tilde{g}} = 30$ GeV/c^2. Also shown is the light constituent background. Both have been subjected to the cuts $X_E < .5$, $P_{out} > 5$ GeV/c, $E_{LEPT} < 2$ GeV.

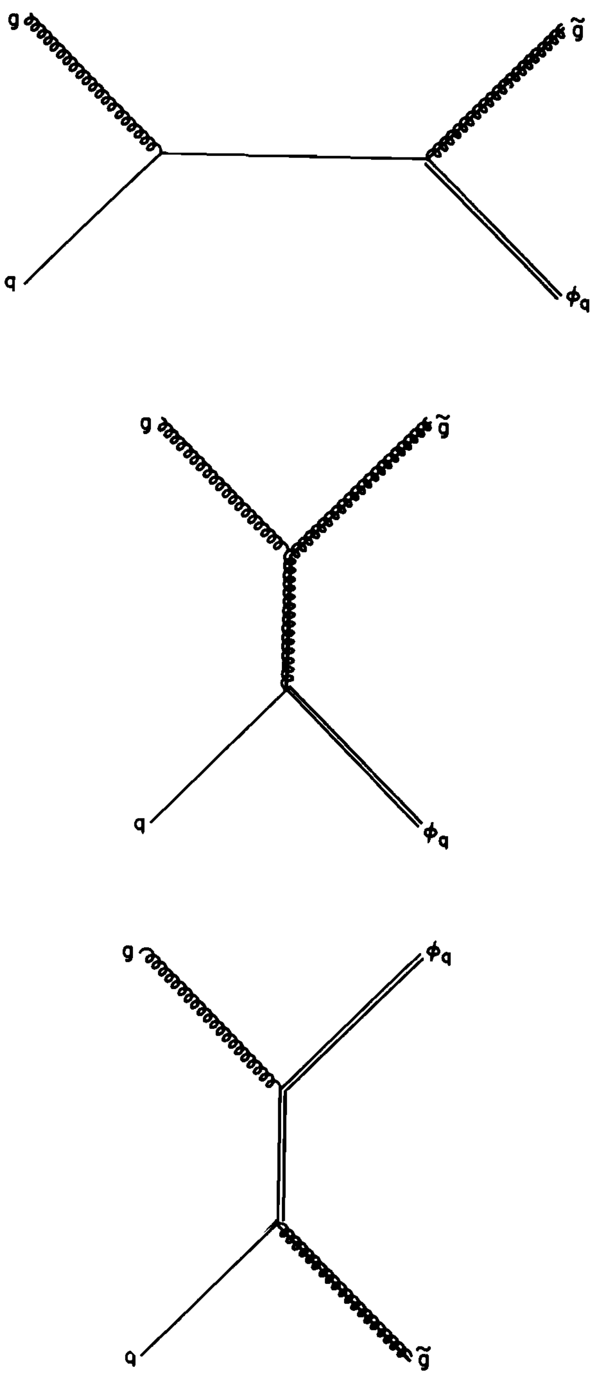

Figure 9. Gluon + quark goes to gluino + scalar quark.

In conclusion, the prospects for detecting the supersymmetric partners of gluons and quarks at a high luminosity 400 × 400 GeV/c pp collider are quite good, if these particles lay in the theoretically interesting mass range $\sim M_W$.

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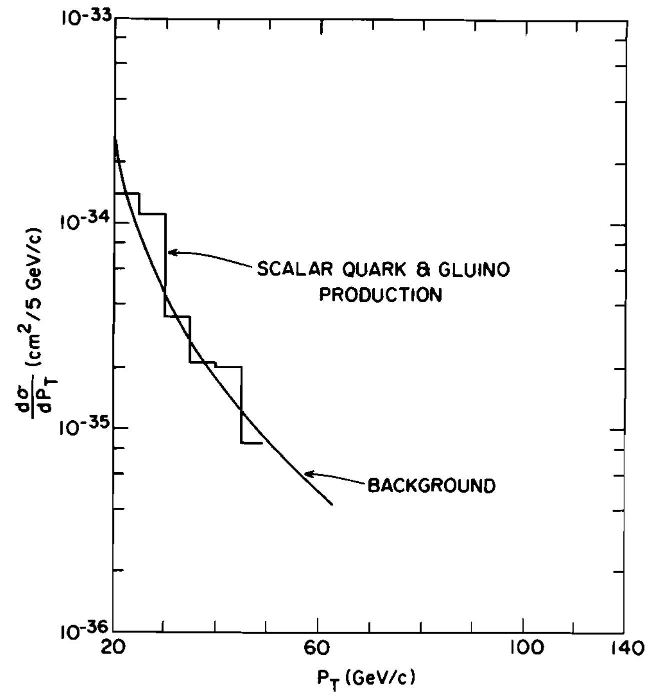

Figure 10. Cross-section vs observed P_T for the process $g + u \to \tilde{g} + \phi_u$ where $M_{\phi_u} = 50$, $M_{\tilde{g}} = 30$ GeV/c. Also shown is the residual background. The cuts $X_E < .5$ and $P_{out} > 5$ GeV/c have been applied to both samples.

References

1. F. Paige and S. Protopopescu, ISAJET: A Monte Carlo Event Generator for ISABELLE, BNL 29777. This paper is based on Version 3.
2. G.L. Kane and J.P. Leveille, Phys. Lett. 112B, 227 (1982), and private communication.
3. All distributions have been calculated for both the two-body and the three-body decay of the gluino. Since it gives slightly more pessimistic results, the three-body decay mode $\tilde{g} \to \tilde{\gamma} q \bar{q}$ has been used in all rate estimates, relative background rejection ratios, etc., and in all the figures of this paper.
4. If the gluino is a Dirac rather than a Majorana particle, the production cross-sections are twice as large as those given in this paper.
5. It is also clear from Fig. 3 that there will be an unacceptable trigger rate of $\sim$ 500/sec for $P_T > 20$ GeV/c at $L = 10^{32}/\text{cm}^2$. One will most likely attempt a partial ON-LINE implementation of the P_T imbalance cuts discussed in the body of this paper. Obviously only a small fraction of the ultimate suppression factor of $\sim$ 18000 need be achieved at the trigger level.
6. A fourth potential background process, $pp \to W + X$, $W \to \tau\nu_\tau$, was also studied. This was found to be less important than the other three, once cuts on kinematic quantitites and on multiplicity were imposed.
7. H.A. Gordon, F.E. Paige, I. Stumer, and C.W. Fabjan R807/note 06 633 (1982) unpublished.
8. J.P. Leveille, private communication.