Gluino-cascade-decay signatures at the Fermilab Tevatron collider

Howard Baer
Physics Department, Florida State University, Tallahassee, Florida 32306

Xerxes Tata
Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822

Jeffrey Woodside
Physics Department, Oklahoma State University, Stillwater, Oklahoma 74078

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As the search for gluinos is extended to higher masses, the gluino cascade decays through lighter gaugino species can no longer be neglected. We compare gluino-cascade-decay signatures with signatures from direct gluino decay to the lightest supersymmetric particle assumed to be massless at the Fermilab Tevatron collider, assuming $m_{\tilde{g}} < m_{\tilde{q}}$. Cascade decays yield a softer missing-p_T ($\not{p}_T$) spectrum which reduces the $\not{p}_T$ cross section by a factor of 2–3 for $m_{\tilde{g}} = 100–150$ GeV. However, new signatures characteristic of the cascade appear in the 0, 1, and 2 lepton plus jets plus $\not{p}_T$ channels. We examine these signatures and compare with dominant standard-model backgrounds.

I. INTRODUCTION

Squarks and gluinos, if they are kinematically accessible, will be copiously produced at hadron colliders[1] such as the CERN $Sp\bar{p}S$ or the Fermilab Tevatron. From a nonobservation of missing-transverse-momentum ($\not{p}_T$) events, the UA1 and UA2 experiments at CERN have announced the limits[2,3]

$$m_{\tilde{g}} > 53 \text{ GeV}, \quad m_{\tilde{q}} > 45 \text{ GeV} \quad (\text{UA1}) , \tag{1a}$$

$$m_{\tilde{g}} > 50 \text{ GeV}, \quad m_{\tilde{q}} > 46 \text{ GeV} \quad (\text{UA2}) . \tag{1b}$$

Since then, the installation of the antiproton accumulator (ACOL) at CERN has at least doubled the data sample. Also, the Collider Detector at Fermilab (CDF) experiment at the Tevatron has accumulated about 5 pb^{-1} of integrated luminosity at $\sqrt{s} = 1.8$ TeV where the $\not{p}_T$ cross section from sparticles is considerably larger than at the CERN collider. This large cross section has already enabled them to considerably improve the CERN bounds (1) on the basis of an analysis of just 25 nb^{-1} of data from which they have extracted the limits[4]

$$m_{\tilde{g}} > 73 \text{ GeV}, \quad m_{\tilde{q}} > 74 \text{ GeV} \quad (\text{CDF}) . \tag{2}$$

In the analyses by which the bounds (1) and (2) are derived, it is explicitly assumed that the produced squarks and gluinos always directly decay to the lightest supersymmetric particle (LSP) which is usually understood to be the photino ($\tilde{\gamma}$). It has, however, been known for some time[5,6] that if the squarks and gluinos are heavy enough to be able to decay into charginos ($\tilde{W}_i$, $i = +, -$) and neutralinos ($\tilde{Z}_{2,3,4}$) other than the LSP ($\tilde{Z}_1$), these decays are likely to dominate the direct decays to the LSP. The LSP that is produced as an end result of the decay of the $\tilde{W}_i$ or $\tilde{Z}_j$ is, on an average, softer than that produced from the direct decay of the squark or gluino. As a result, the fraction of gluino or squark events that pass the $\not{p}_T$ cut is considerably reduced if the cascade decays dominate the direct decays. This, in turn, may reduce the lower bound on $m_{\tilde{g}}$ or $m_{\tilde{q}}$ that may be obtained from the $\not{p}_T$ analysis.

These considerations motivated us[7] to study the $\not{p}_T$ signal from squarks and gluinos that might be observed at the Fermilab Tevatron. We found that the cascade decays could reduce the bound (2) on the gluino mass by as much as 30 GeV. The dominant reduction was due to the large branching fraction for the decay $\tilde{g} \to q\bar{q}\tilde{W}_-$. The effect of the cascade decays on the squark-mass bound (2) was found to be much smaller. This was traced to the fact that the weak isosinglet right-handed squarks cannot decay into charginos, as a result of which over half the squark pairs decay directly to the LSP. Thus, the effect of the cascades on the squark bound (2) is much less significant, reducing $m_{\tilde{q}}$ by typically 10 GeV. An earlier study[5] of the effect of cascade decays on squark and gluino masses accessible to the CERN data concluded that the bounds (1) would change only by a few GeV.

The cascade decays of squarks and gluinos will assume increased importance as higher values of their mass are probed[8] at the Tevatron. Apart from the reduction of the $\not{p}_T$ spectrum and the resulting effect on the mass bound discussed earlier, these cascade decays also result in several new potential signals for supersymmetry. This is especially true for the gluino since, as discussed above, only about 50% of the squarks decay to heavier gauginos. For this reason we will focus on signals from gluino pair production.

We also note that if squarks are much lighter than gluinos, the renormalization-group evolution drives $m_{\tilde{q}}^2$ to negative values before the unification scale[9] unless one introduces new Yukawa couplings not present in the minimal model. Hence, for definiteness, we will assume that $m_{\tilde{q}} > m_{\tilde{g}}$ and confine our discussion to signals from $\tilde{g}\tilde{g}$ production that may be accessible to the Tevatron. If $m_{\tilde{q}} \simeq m_{\tilde{g}}$ there will be additional signals from $\tilde{q}\tilde{q}$ and $\tilde{g}\tilde{q}$ production. Also, if $m_{\tilde{q}} < m_{\tilde{g}}$, the squark mediating gluino decays will be dominantly on mass shell so that gluinos will then act as sources of squarks. These additional signals and the modification to the gluino decay pattern if $m_{\tilde{q}} < m_{\tilde{g}}$ will be discussed elsewhere.[10]

Our analysis is performed within the framework of the minimal supergravity model[11] which may be the basic theory, or more likely, be the effective theory relevant at present energies that is derived from a more fundamental theory. This assumes that only the minimal field content is relevant. We then survey those regions of the parameter space which give gluinos with masses accessible at the Tevatron and with $m_{\tilde{q}} > m_{\tilde{g}}$, and find that gluino decays to charginos and neutralinos other than the LSP play an important role in the analysis for $m_{\tilde{g}} \gtrsim 100$ GeV. In the future, it may be possible to derive these parameters from more basic considerations, but for the purposes of phenomenological analysis, it suffices to treat them as arbitrary.

The signal from gluino pair production under the assumption of the "naive" $\tilde{g} \to q\bar{q}\tilde{Z}_1$ decays contains at most four jets (apart from QCD radiative corrections). In contrast, the cascade decays can lead to events with much larger jet multiplicity. For instance, the two-step cascade $\tilde{g} \to q\bar{q}\tilde{W}_-$, $\tilde{W}_- \to q\bar{q}\tilde{Z}_1$ can lead to as many as eight jets from a gluino-pair event. In addition to these high-multiplicity multijet$+\not{p}_T$ events, the leptonic decays of the $\tilde{W}/\tilde{Z}$ produced in gluino decays lead to n jet$+m$ lepton$+\not{p}_T$ event topologies. A particularly striking class[12] of these events arises from the decay of each gluino into a chargino of the same sign; the leptonic decay of the charginos then leads to isolated, same-sign dilepton events which should be distinct above the background. Thus, apart from the canonical $\not{p}_T$ signal for gluino pair production, there are several other potential signals expected from gluino pairs. Observation of events in each of the allowed channels at expected rates would lead to a spectacular confirmation of the predictions of the minimal supergravity model.

The rest of this paper is organized as follows. In Sec. II we briefly review the decay patterns of the gluino as well as of charginos and neutralinos that are relevant for the computation of signals at the Tevatron. In Sec. III we calculate the jets$+\not{p}_T$ signal expected at the Tevatron incorporating realistic decay patterns of the gluino as given by the minimal model. We compare these signals with the corresponding rates for $\not{p}_T$ events that would be obtained assuming that gluinos can only decay to $\tilde{Z}_1$. Standard-model (SM) backgrounds are also calculated. We find that the 5-jet$+\not{p}_T$ signal gives the greatest reach in gluino mass at a high-luminosity Tevatron. In Sec. IV, we discuss the prospects for separating the 1 lepton$+n$ jets$+\not{p}_T$ signal from gluinos from the SM backgrounds which come primarily from $W+$jets and heavy-flavor production. Dilepton signals are discussed in Sec. V. It is emphasised that the same-sign dilepton cross section is large enough to yield a small but background-free signal at a high-luminosity machine. There is also a signal from opposite-sign dileptons plus jets which is obscured by the possible background from top-quark pair production. Section VI contains a summary of our results. A preliminary report of some of the results of this paper may be found in our contribution to the 1988 Snowmass Proceedings.[12]

II. DECAY PATTERNS OF GLUINOS, CHARGINOS, AND NEUTRALINOS

Since the gluino has only strong interactions, it can only decay via $\tilde{g} \to q\tilde{q}$, where the squark may be real or virtual depending on its mass. Within the framework of the minimal supergravity model,[11] squark and slepton masses satisfy, apart from D-term contributions,

$$m_{\tilde{q}}^2 \simeq m_{\tilde{l}}^2 + 0.8 m_{\tilde{g}}^2 , \tag{3}$$

which, in turn, implies that the squark can never be much lighter than the gluino.[13] The gluino, therefore, almost aways decays via

$$\tilde{g} \to q\bar{q}\tilde{Z}_i \tag{4a}$$

or

$$\tilde{g} \to q\bar{q}\tilde{W}_j , \tag{4b}$$

where the $\tilde{Z}_i$ and $\tilde{W}_j$ denote the neutralinos and charginos lighter than the gluino. Note that the assumption that the $\tilde{Z}_1$ is the LSP implies that the decay

$$\tilde{g} \to q\bar{q}\tilde{Z}_1 \tag{5}$$

is always allowed. The bounds (1) and (2) were obtained under the assumption that this is the only allowed decay mode of the gluino.

The branching fractions for the decays (4) depend on the masses as well as the couplings of the charginos and neutralinos to the virtual squarks mediating gluino decay. These, in turn, are determined by the model-dependent mass matrices in the electroweak gaugino-Higgsino sector. In the framework of the minimal supersymmetric model with a common gaugino mass at the unification scale, these mass matrices are completely determined in terms of three additional parameters which may be taken to be (i) the gluino mass $m_{\tilde{g}}$, (ii) $2m_1$, the supersymmetric Higgsino mass, and (iii) the ratio v'/v of the vacuum expectation values of the two Higgs fields that give rise to the masses of the $T_3 = \pm\frac{1}{2}$ fermions. For the minimal model, the branching fractions have been extensively studied in the literature.[5,6,8,14,15] Here, we merely review some of the salient features necessary for our analysis.

(1) The branching fraction for the direct $\tilde{g} \to q\bar{q}\tilde{Z}_1$ decay is shown in Fig. 1 for several gluino masses. We see that even for $m_{\tilde{g}} = 80$ GeV, a value very near the Tevatron mass bound (2), and modest values of $2m_1$, it is significantly smaller than unity. This feature is insensitive to the value of v'/v which is taken to be $v'/v = \frac{2}{3}$ in this figure.

(2) The decays to charginos dominate those to neutralinos (including the LSP) if they are kinematically accessible. This was traced to the fact that the SU(2) gauge cou-

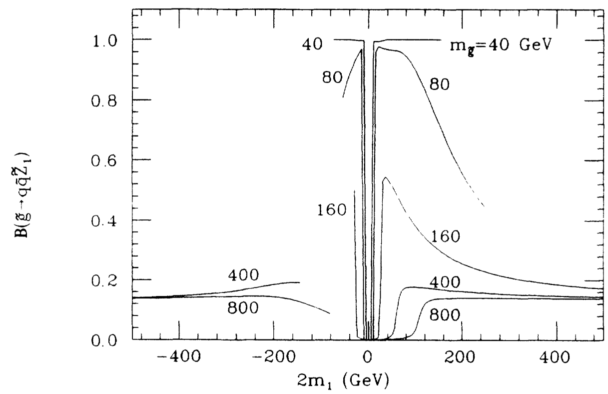

FIG. 1. The branching fraction for the direct decay of the gluino to the LSP vs the supersymmetric Higgsino mass $2m_1$ for several values of $m_{\tilde{g}}$. We assume here that $v'/v=\frac{2}{3}$ and $m_{\tilde{q}}=2m_{\tilde{g}}$. The gaps in the curves denote regions where $m_{\tilde{W}_-}<40$ GeV.

pling significantly exceeds the $U(1)_{EM}$ or $U(1)_Z$ couplings. For a quantification of the branching ratios for gluino decays into the various chargino and neutralino modes, we refer the reader to Refs. 14 and 15.

(3) For very small values of $|2m_1|$ the LSP is almost a Higgsino so that the decay $\tilde{g}\to q\bar{q}\tilde{Z}_1$ is strongly suppressed by the tiny Yukawa coupling factors. In this case, apart from the decays $\tilde{g}\to q\bar{q}\tilde{Z}_2$ ($\tilde{Z}_2\approx\tilde{\gamma}$), the decay $\tilde{g}\to\tilde{Z}_1+g$ mediated by top family loops can be significant.[16] This radiative decay rate depends on the top sfamily parameters but is typically important for $|2m_1|<15$ GeV and $m_{\tilde{g}}<70$ GeV. In our analysis we have ignored this decay mode. This is permissible as long as $\tilde{Z}_1$ is not almost completely a Higgsino.

Next we turn to the decays of charginos and neutralinos resulting from the decays (4) of the gluino. In the minimal model, there are two charginos ($\tilde{W}_-$ and $\tilde{W}_+$ with $m_{\tilde{W}_-}<m_{\tilde{W}_+}$) and four neutralinos ($\tilde{Z}_{1,2,3,4}$ in order of increasing mass) which decay via

$$\tilde{Z}_j\to\tilde{Z}_i+(Z \text{ or } P, H^0_{l,h}) ,$$
$$\tilde{Z}_j\to\tilde{W}_i+(W \text{ or } H^{\pm}) , \tag{6a}$$

or

$$\tilde{Z}_j\to\tilde{f}+f , \tag{6b}$$

and

$$\tilde{W}_j\to\tilde{Z}_i+(W \text{ or } H^{\pm}) ,$$
$$\tilde{W}_+\to\tilde{W}_-+(Z \text{ or } P, H^0_{l,h}) , \tag{7a}$$
$$\tilde{W}_j\to\tilde{f}+f . \tag{7b}$$

Here, $H^0_{l,h}$ and P, respectively, denote the neutral scalars and pseudoscalar of the Higgs-boson sector[17] of the minimal model. $H^{\pm}$ denotes the charged Higgs bosons and $(f,\tilde{f})$ a sfermion family with $f=(q, l, \text{or } \nu)$. In Eqs. (6) and (7), the gauge bosons, Higgs bosons, and sfermions may be either real or virtual. If any of the two-body decays are kinematically accessible, they almost always dominate the three-body decays mediated by a virtual boson.[18] The relevant formula and numerical branching fractions may be found in Refs. 14 and 19.

In this paper, we have taken the squark to be heavy compared to the gluino. This is realized by taking the supersymmetry-breaking scalar masses much larger than the gaugino and gauge-boson masses. Within the framework of supergravity models,[11] there is a universal scalar mass. Thus choosing the squarks very heavy has the consequence that the Higgs bosons H_h, P, and $H^{\pm}$ all become very heavy and the lighter Higgs boson H_l almost behaves as the SM Higgs scalar. In our computation, we have taken $m_{H^+}=0.5$ TeV though our results are almost independent of this specific value as long as it is large.

The following points are worthy of note.

(i) The heavier chargino and the heavier neutralinos $\tilde{Z}_{3,4}$ almost always decay via two-body modes. However, their production rate from the decays of gluinos at the Tevatron is small.

(ii) The lighter chargino can only decay via $\tilde{W}_-\to q\bar{q}\tilde{Z}_1$ or $l\nu\tilde{Z}_1$ where these decays may be mediated by the virtual W or sfermion $\tilde{f}$. In our calculation where we have assumed $m_{\tilde{q}}\approx m_{\tilde{l}}\approx m_{\tilde{\nu}}\gg m_{\tilde{g}}$, the W-mediated process dominates so that the branching ratios are just that of the W: i.e., 11% per lepton family.

(iii) The decay of $\tilde{Z}_2$ is very model dependent. For a large range of parameters, the decay $\tilde{Z}_2\to\tilde{Z}_1+H^0_l$ is accessible since H^0_l is expected to be relatively light (recall that $m_{H_l}=0$ for $v'/v=1$). The branching fraction for $\tilde{g}\to q\bar{q}\tilde{Z}_2$ almost never exceeds 0.2 so that this dependence is never very significant in our analysis.

This completes our summary of the decay patterns of the sparticles. Any gluino produced at the Tevatron decays into a $\tilde{W}_i$ or $\tilde{Z}_i$ which, in turn, decays via (6) or (7), unless $\tilde{Z}_i=\tilde{Z}_1$. This decay cascade terminates in the stable LSP ($\tilde{Z}_1$). We have constructed an event generator for gluino production and decay which incorporates the complete cascade decay of the gluino, i.e., Eqs. (4)–(7), as given by the minimal model. The variety of decays of the gluino, chargino, and neutralino leads to a corresponding variety in the signals from gluino pair production at the Tevatron, a study of which forms the subject of the rest of this paper.

III. NONLEPTONIC SIGNALS FROM GLUINO PAIRS

As discussed in the previous section gluinos in the mass range being probed at the Tevatron are likely to have substantial branching fractions into charginos and neutralinos other than the LSP. If the chargino (or neutralino) then decays into $q\bar{q}\tilde{Z}_1$, this two-step decay of the gluino then leads to two primary quarks, two secondary quarks, and the LSP, which escapes detection. Thus a gluino pair event, with both gluinos decaying hadronically via this two-step process, can in principle lead to 8 jet$+\not{p}_T$ events. In practice, the number of jets in these events is smaller because of calorimeter segmentation and jet acceptance criteria. This is to be contrasted with gluino-pair-production events where the gluinos decay directly to the LSP; these events, apart from QCD corrections, contain at most four jets. Of course, in events where the gluino decays in more than two steps an even larger number of jets is possible, although many of these may be too soft to satisfy jet acceptance criteria.

To evaluate these multijet$+\not{p}_T$ event rates, we have constructed a Monte Carlo generator to simulate the final state from gluino pair production with the predicted cascade decays, including supersymmetric-particle masses and mixings as given by minimal supergravity. In our calculations, we have attempted to simulate the CDF experimental conditions as follows.

(1) We identify jets with partons. We coalesce partons within $\Delta R=\sqrt{\Delta\eta^2+\Delta\phi^2}<0.7$ into single jets. We also require that all the jets satisfy $|\eta_j|<2.5$, and each jet must have $E_T>15$ GeV. The highest E_T cluster is also required to be central ($|\eta|<1$).

(2) We require that there be no jet with $E_T>5$ GeV within a 30° cone back to back in azimuth with the leading jet.

(3) We require

$$\not{E}_T > \max\left[50\text{ GeV}, 2.8\times\sqrt{\sum E_T}\right],$$

where $\sum E_T$ is the total scalar transverse energy in the event, including a soft-scattering E_T contribution.

The cross section[1] for gluino pair production is determined in terms of $m_{\tilde g}$ and $m_{\tilde q}$ (which enters via the t-channel propagator in $q\bar q\to\tilde g\tilde g$) by color gauge invariance and supersymmetry. The decay patterns of the gluino, however, depend on all the parameters of the gaugino-Higgsino mixing matrix as discussed in Sec. II. Thus the complete characterization of signals from gluino pair production requires the specification of five input parameters ($m_{\tilde g}$, $m_{\tilde q}$, $2m_1$, v'/v, and m_{H^+}) with the results being insensitive to m_{H^+} as long as it is large.

The $\not{p}_T$ spectrum from gluino pairs before cuts is shown[20] by the solid curves in Fig. 2 for $m_{\tilde g}=100$ GeV. In this calculation, we have fixed $m_{\tilde q}=2m_{\tilde g}$, $v'/v=\frac{2}{3}$, $2m_1=150$ GeV, and $m_{H^+}=500$ GeV. The dashed curve in the figure shows the corresponding $\not{p}_T$ distribution that is obtained if only the direct $\tilde g\to q\bar q\tilde Z_1$ decays are allowed, with $m_{\tilde Z_1}=0$. Clearly, the fraction of events that satisfy the CDF $\not{E}_T$ requirement[4] is substantially reduced when the cascades are included. This is primarily the reason for the reduction[7] in the gluino-mass bound from the value reported in Ref. 4.

The cross sections for n jet$+\not{p}_T$ event topologies from gluino pair production are shown in Fig. 3 with cascade decays (solid lines) and with only direct $\tilde g\to q\bar q\tilde Z_1$ decays (dashed lines) where $m_{\tilde Z_1}=0$. In this calculation the cuts (1)–(3) are all imposed and the SUSY parameters fixed as in Fig. 2. The following features of Fig. 3 are worth noting.

(1) The cross section for $n\geq 5$ jets assuming direct gluino decays is zero whereas the cascade decays allow the corresponding cross sections to approach 1 pb.

(2) Whereas dijet events dominate for lower values of $m_{\tilde g}\sim 50-90$ GeV, four-jet events dominate for $m_{\tilde g}>140$ GeV assuming realistic decays. In the case of direct gluino decays, four-jet topologies dominate only when $m_{\tilde g}>250$ GeV.

(3) The cascade decays lead to a reduction of the 1–4 jet$+\not{p}_T$ cross section by a factor of about 3 for $m_{\tilde g}<150$ GeV (and by even a larger factor for heavier gluinos) as compared with the case of the direct decay of the gluino.

Neutrinos produced via the decay of intermediate vector bosons ($W^\pm, Z^0$) and top quarks are the major source of large $\not{p}_T$ in the SM. The leading backgrounds to the gluino $\not{p}_T$ signal come from (a) $Z\to\nu\bar\nu$+jets, or $W\to\tau\nu$+jets, and (b) $t\bar t$ production, where at least one of the top quarks decays semileptonically. Since we are focusing on nonleptonic gluino decays, we have vetoed

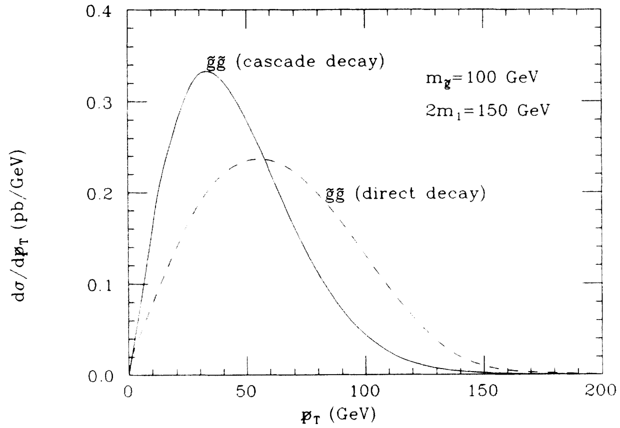

FIG. 2. A comparison of the $\not{p}_T$ spectrum from gluino pair production at the Tevatron with realistic gluino cascade decays (solid line) and only direct decays to a massless LSP (dashed lines). The SUSY parameters are fixed at $m_{\tilde g}=100$ GeV, $2m_1=150$ GeV, $v'/v=\frac{2}{3}$, and $m_{\tilde q}=2m_{\tilde g}$.

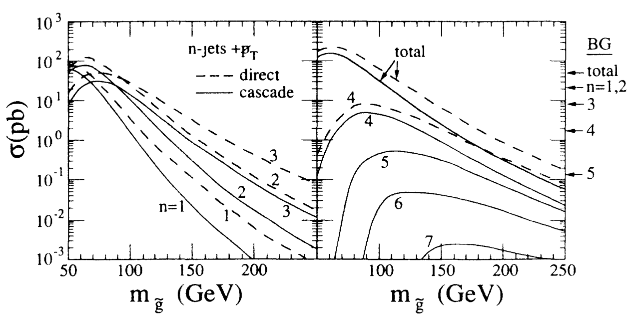

FIG. 3. Expectations for 0 lepton$+n$ jets$+\not{p}_T$ cross sections from gluino pair production with cascade decays (solid curves) and with only direct decays to a massless LSP (dashed curves), as a function of $m_{\tilde g}$. The cuts are as described in Sec. III, and the parameters are as in Fig. 2. The arrows denote the sum of the SM backgrounds for each event topology from the sources shown in Table I, assuming $m_t=75$ GeV.

background events where there is an identified e or μ, where we assume that isolated electrons and muons satisfying

$$|p_{Te}|>10 \text{ GeV}, \quad |p_{T\mu}|>5 \text{ GeV} , \tag{8a}$$

$$|\eta_e|<3, \quad |\eta_\mu|<0.76 , \tag{8b}$$

$$\sum E_T<3 \text{ GeV} \text{ in } \Delta R=0.4 \text{ about the electron} \tag{8c}$$

are identified. For the purpose of vetoing, we have also assumed that an electron inside a "jet" ($\Delta R_{ej}<0.7$) can be identified if

$$|p_{Te}|>4|p_{Tj}| . \tag{8d}$$

The backgrounds from $W \to e,\mu+\nu$ as well as from $b\bar{b}$ production give a very small cross section for a high-p_T neutrino and a soft charged lepton. The lepton veto removes these as well as a substantial fraction of $t\bar{t}$ events. For the computation of the W,Z +jets cross sections we have used the shower Monte Carlo method described in Ref. 22.

Our results from these calculations are shown in Table I for $m_t=75$ and 125 GeV. We see that the vector bosons are the dominant backgrounds for number of jets $n_j \le 2$ while higher jet multiplicity backgrounds come mainly from $t\bar{t}$. We note the following.

(i) The monojet topology, so useful in searching for gluinos at the CERN $p\bar{p}$ collider, is well below the expected background for $m_{\tilde{g}} \gtrsim 70-80$ GeV, i.e., for most of the gluino mass range being probed[4] by the Tevatron. Dijet topologies exceed the SM background only up to $m_{\tilde{g}} \simeq 100$ GeV. The backgrounds in these channels would be somewhat reduced if it would be possible to identify the τ jets in $W \to \tau\nu$ decay.

(ii) The three-jet topology seems to be the optimal one for a gluino search if $m_{\tilde{g}}<100$ GeV. The $\not{p}_T$ cross section after all the cuts exceeds ~ 20 pb whereas our estimates indicate that the SM background is smaller than ~ 8 pb even if m_t is as low as 75 GeV.

(iii) Gluinos heavier than ~ 100 GeV can best be searched for in the four- and five-jet topologies. In this case, the dominant background comes from t quarks. For $m_{\tilde{g}}$ up to ~ 150 GeV, the 4 jet$+\not{p}_T$ cross section exceeds ~ 2 pb and is above the SM background. In the five jet channel, the signal/background exceeds unity for $m_{\tilde{g}} \lesssim 170-180$ GeV but for such heavy gluinos, the cross section is only ~ 0.25 pb so that it may only be possible to search for these with $\int L\,dt \sim 50-100$ pb^{-1}. With a high-luminosity Tevatron upgrade such as discussed at the 1988 Snowmass workshop,[21] gluino masses up to ~ 200 GeV should be accessible. These signal/background ratios can be considerably larger depending on the squark mass. We have shown in Fig. 4 the dependence of the total gluino pair production cross section on $m_{\tilde{q}}$ over the range of $m_{\tilde{g}}$ of interest to the Tevatron. We show curves for $m_{\tilde{q}}=2m_{\tilde{g}}$, $m_{\tilde{q}}=m_{\tilde{g}}$, $m_{\tilde{q}}=500$ GeV, and $m_{\tilde{q}}=1000$ GeV. In this range of parameters, a 200-GeV gluino pair cross section can vary by a factor of ~ 5. It is interesting to note that $\sigma(\tilde{g}\tilde{g})$ increases as $m_{\tilde{q}}$ increases. This is due to a reduction of destructive interference between the production diagrams involving initial-state quarks.

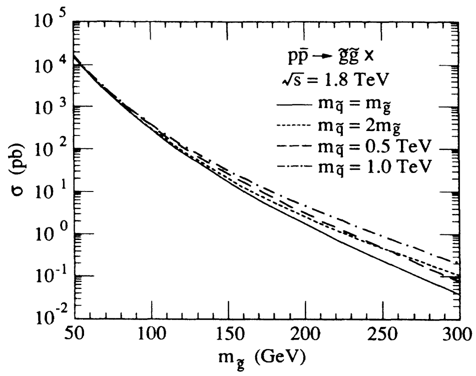

FIG. 4. The total $\tilde{g}\tilde{g}$ cross section in $p\bar{p}$ collisions at $\sqrt{s}=1.8$ TeV for $m_{\tilde{q}}=m_{\tilde{g}}$ (solid), $m_{\tilde{q}}=2m_{\tilde{g}}$ (dotted), $m_{\tilde{q}}=500$ GeV (dashed), and $m_{\tilde{q}}=1000$ GeV (dotted-dashed) vs $m_{\tilde{g}}$.

(iv) The cascade decays significantly reduce the mass reach of the Tevatron in the $\not{p}_T$ channel. For instance, the signal/background for four jets$+\not{p}_T$ is equal to unity for $m_{\tilde{g}}=140-150$ GeV with cascade decays. With direct decays, signal/background equals unity for $m_{\tilde{g}}=210-240$ GeV.

Shown in Fig. 5 is the scalar transverse energy in signal events for $m_{\tilde{g}}=100$ (150) GeV for three (four) or more jets. Also shown is the scalar E_T from various SM

TABLE I. A tabulation of dominant backgrounds to 0 lepton$+n$ jets$+\not{p}_T$ gluino pair signals, with the cuts of Sec. III.

n_j	Z	$W \to \tau$	$t\bar{t}$ (75)	$t\bar{t}$ (125)	Total (75)	Total (125)
1	13	4	5	0.2	22	17
2	8	6	7	0.7	21	15
3	1	2	5	1	8	4
4	0.05	0.2	2	0.7	2	1
5	0.004	0.02	0.1	0.2	0.1	0.2
Total	22	12	19	3	53	37

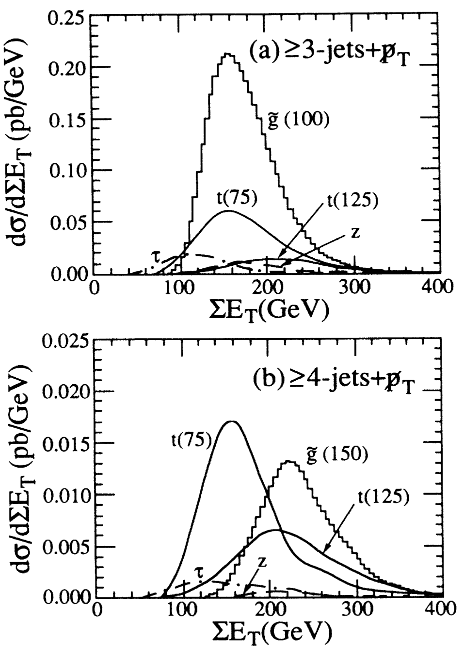

FIG. 5. The total scalar E_T distribution for (a) ≥ 3 jets$+\not p_T$ events for $m_{\tilde{g}}=100$ GeV, and (b) for ≥ 4 jets$+\not p_T$ events for $m_{\tilde{g}}=150$ GeV, with cuts as discussed in Sec. III. Also shown are the same distributions from the following SM sources: $W\to\tau\nu$+jets (dotted-dashed), $Z\to\nu\bar{\nu}$+jets (dashed), and from $t\bar{t}$ production for $m_t=75$ and 125 GeV where the lepton from top decays escapes identification (solid).

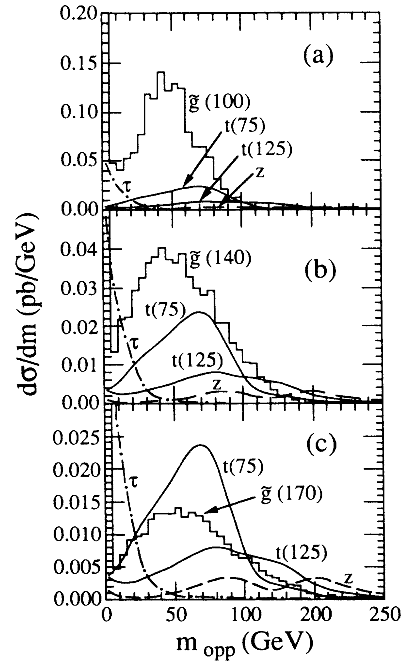

FIG. 6. The invariant-mass distribution of jets in an azimuthal cone of 120° opposite the $\not p_T$ vector in 0 lepton$+\geq 3$ jet$+\not p_T$ events from gluino pairs (histogram), $t\bar{t}$ events (solid) ($m_t=75$,125 GeV), $W\to\tau$+jets (dotted-dashed), and $Z\to\nu\bar{\nu}$+jets (dashes) for (a) $m_{\tilde{g}}=100$ GeV, (b) $m_{\tilde{g}}=140$ GeV, and (c) $m_{\tilde{g}}=170$ GeV. In this figure, we also require $\not p_T>75$ GeV.

sources. For $m_{\tilde{g}}=100$ GeV the signal is typically 3–4 times larger than background and should be easily observable. For the heavier gluino case, a higher signal/background ratio is obtained by requiring higher jet multiplicity ($n\geq 4$); in this case there are as many events from a 75-GeV t quark as from the signal but requiring $\sum E_T>200$ GeV reduces the background by roughly a factor of 4 with little loss of signal.

We have also considered the possibility of measuring the gluino mass in these events. This is complicated because each gluino pair event contains at least two undetected massive particles. A possible strategy is to select out hemispherically separated $\tilde{g}\tilde{g}$ events where one of the gluinos decays directly to the LSP while the other decays via a cascade. The invariant mass of the hadronic decay products of the gluino is bounded by $m_{\tilde{g}}-m_{\tilde{Z}_1}$.

In an attempt to achieve this, we have required $\not p_T>75$ GeV. This ensures that, of the events where only one gluino decays directly to the LSP, the gluino should have large p_T, and the event is more likely separated in hemispheres. We have plotted in Figs. 6(a)–6(c) the invariant mass of the jet system in a 120° cone opposite $\not p_T$ for $m_{\tilde{g}}=100$, 140, and 170 GeV. In order to minimize SM backgrounds, we have only included events with ≥ 3 jets. There is some correlation of the distribution end point with $m_{\tilde{g}}-m_{\tilde{Z}_1}$, but background processes smear this. A rough determination of $m_{\tilde{g}}$ may be possible, especially if $m_{\tilde{g}}<140$ GeV. Cross sections after cuts for $m_{\tilde{g}}=100$, 140, 170 GeV are 8.5, 3.7, 1.5 pb, respectively, so a large data sample (~ 100 pb^{-1}) would be required.

IV. ONE LEPTON PLUS JETS PLUS $\not p_T$ SIGNALS

As discussed in Sec. II, the gluino dominantly decays via $\tilde{g}\to q\bar{q}\tilde{W}_-$ unless this decay is kinematically suppressed. Apart from phase-space effects the chargino decay mode has a branching fraction of ~ 0.5. Folding this with the $\tilde{W}_-$ leptonic branching fraction into e or μ, we conclude that as many as $\sim 2\times 0.5\times 0.22$, or about one-fifth of the produced gluino pairs will contain a fast, isolated lepton in their decay products. Such signatures are, of course, absent if the gluino can only decay directly to the LSP.

We require the following acceptance criteria:

$$p_T(e,\mu)>20 \text{ GeV}, \quad |\eta(e)|<3.0, \quad |\eta(\mu)|<0.76 \; ; \tag{9a}$$

isolation

$$\sum E_T<3 \text{ GeV} \quad \text{in cone } \Delta R<0.4 \tag{9b}$$

about the lepton momentum;

$$\not p_T>20 \text{ GeV} \; , \tag{9c}$$

$$p_T(\text{jet})>15 \text{ GeV}, \quad |\eta(\text{jet})|<2.5 \; . \tag{9d}$$

These cuts eliminate the bulk of the backgrounds from $b\bar{b}$

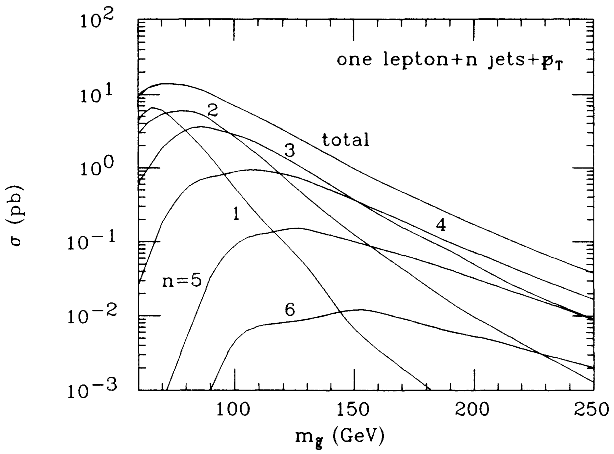

FIG. 7. Expectations for the 1 lepton$+n$ jets$+\not{p}_T>20$ GeV cross sections at the Tevatron with cuts as given in Sec. IV, and backgrounds in Table II. SUSY parameters are fixed as in Fig. 2.

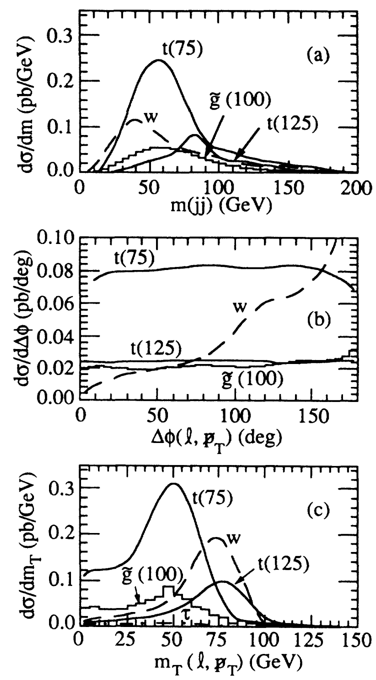

FIG. 8. Distributions for (a) the invariant mass of the two highest-p_T jets, (b) the azimuthal opening angle between the lepton $\mathbf{p}_T$ and $\not{p}_T$, and (c) the transverse mass $M_T(l,\not{p}_T)$ in the single-lepton events of Fig. 7, where we restrict $n\,(\text{jets})\geq 3$ and $m_{\tilde{g}}=100$ GeV. Also shown are the corresponding distributions from SM sources: $W\to l\nu+$jets (dashes), $W\to\tau\nu+$jets, $(\tau\to l)$ (dotted-dashed) and $t\bar{t}$ production (solid) for $m_t=75$ and 100 GeV.

and $c\bar{c}$ production, but leave a non-negligible signal, plus large background contributions from ordinary $W+$jet production, $W\to\tau\nu\to l\nu\bar{\nu}\nu$ and $t\bar{t}$ production. In fact, these are precisely the kind of cuts one uses for selecting ordinary W events.[23]

In Fig. 7 we show the resulting cross sections for 1 lepton$+n$ jets$+\not{p}_T$ events from gluino pairs expected at the Tevatron, plotted as a function of $m_{\tilde{g}}$. The other supersymmetry (SUSY) parameters are fixed as in Sec. III. For $m_{\tilde{g}}<100$ GeV, one lepton plus dijet topologies dominate. As $m_{\tilde{g}}$ increases, trijet topologies dominate until for $m_{\tilde{g}}>150$ GeV, four-jet topologies are dominant. These one-isolated lepton plus jet topologies all occur with rates typically less than 10 pb.

The background rates for these topologies have been calculated in Ref. 24 and are summarized in Table II. Even the largest signal rates for one lepton plus a monojet are below backgrounds by factors exceeding 30. As we move to higher jet multiplicity, the signal/background ratio improves and approaches unity for $n\,(\text{jets})\geq 4$.

Some optimization of selection cuts is required to see a gluino signal in the fast isolated lepton$+n$ jet$+\not{p}_T$ channel. Clearly, any hope of seeing a signal will require $n\geq 3$ or 4. For high jet multiplicity, the dominant background will likely come from $t\bar{t}$. In Fig. 8(a) we plot the invariant mass of the two fastest jets in 1 lepton$+n\geq 3$ jet events from $\tilde{g}\tilde{g}$ production with $m_{\tilde{g}}=100$ GeV. If $t\to b+W$ where W is real, then top-quark events will contain two jets with mass reconstructing M_W. This is generally not the case for gluino-pair events, and some sort of veto on high-mass top quarks can be achieved. In Fig. 8(b) we plot the azimuthal lepton $\mathbf{p}_{Tl}$-$\not{p}_T$ opening angle for a 100-GeV gluino, and the dominant backgrounds. A selection on $\Delta\phi(l,\not{p}_T)\lesssim 90°$ can help eliminate a greater proportion of $W\to l\nu$ backgrounds.

TABLE II. A tabulation of dominant backgrounds to 1 lepton$+n$ jets$+\not{p}_T$ gluino pair signals, with the cuts of Sec. IV.

n_j	W	$W\to\tau$	$t\bar{t}$ (75)	$t\bar{t}$ (125)	$b\bar{b}$	Total (75)	Total (125)
1	300	9	10	1	0.3	319	310
2	60	2	20	2	10	92	74
3	7	0.3	10	3		17	10
4	0.6	0.02	3	2		4	3
5	0.01		0.2	0.2		0.2	0.2
Total	368	11	43	8	10	432	397

It has been pointed out that a signal for top quarks may be found by looking for an enhancement in the transverse-$l\nu$-mass $[M_T(l,\not{p}_T)]$ distribution of lepton$+n\geq 3$ jet events for $m_t<M_W$ (Ref. 24). If $m_t>M_W+m_b$, then the $M_T(l,\not{p}_T)$ distributions from $t\bar{t}$ and $W\to l\nu$ events are very similar: both rise to a Jacobian peak at $M_T=M_W$. We plot in Fig. 8(c) the $M_T(l,\not{p}_T)$ distribution from a 100-GeV gluino, and also from W and $t\bar{t}$ backgrounds. The gluino signal rises to a peak at $M_T\sim 50$ GeV and may thus be visible in an ordinary sample of $W\to l\nu+3$ jet events provided $m_{\tilde{g}}\lesssim 120$ GeV, and top decays to a real W boson.

Signal rates in the one-lepton channel are only at the few pb level, so 50–100 pb^{-1} of data will be required. However, backgrounds in this channel are severe, and depending on the top-quark mass, may be insurmountable. If a signal is observed, events of this type could also be the first evidence of chargino production if $\widetilde{W}_-$ is too heavy to be produced at LEP or SLC.

V. DILEPTON PLUS JET PLUS $\not{p}_T$ SIGNALS

Dileptons from gluino pairs mostly come from $\tilde{g}\to q\bar{q}\widetilde{W}_-$ decays of both gluinos where each chargino decays leptonically.[12] Modulo phase-space suppression, we may expect $\sim(0.5)^2\times(0.22)^2\simeq 1\%$ of the total number of gluino pair events to contain two leptons (e or μ). A smaller number of such events can be expected from $\tilde{g}\to q\bar{q}\widetilde{Z}_2$, $\widetilde{Z}_2\to l\bar{l}\widetilde{Z}_1$ decays. In this case, the two leptons always have the same flavor and opposite electric charge whereas half the dilepton events from chargino decays of the gluino contain a like-charge lepton pair. This is a characteristic of the Majorana nature of the gluino.[12]

In our simulation of the dilepton signal we have reduced the p_T requirement on each lepton to

$$|p_{Tl}|>15 \text{ GeV} . \qquad (10)$$

Each lepton is required to be within the angular acceptance (8b) and both leptons are required to satisfy the isolation criterion (8c). This reduces the dilepton contribution from the production of $c\bar{c}$ and $b\bar{b}$ pairs. We further require

$$|\not{p}_T|>20 \text{ GeV} \qquad (11)$$

to reduce the γ^*, $Z\to l^+l^-+$"jets" background. Finally, we impose an azimuthal angle cut

$$30^\circ\leq\Delta\phi(l^+l^-)\leq 150^\circ \qquad (12)$$

to eliminate lepton pairs from Drell-Yan production and Z^0 decays.

With these cuts, $t\bar{t}$ production followed by the semileptonic decays of both top quarks is the dominant SM source of dilepton pairs.[25] W pair production with $W\to l\nu$ and γ^*, $Z\to\tau\bar{\tau}$ with $\tau\to l\bar{\nu}\nu$ make a much smaller contribution[25] for $m_t<160$ GeV. Note that of these only the $t\bar{t}$ events really constitute a serious background since the cross section for vector-boson-initiated dilepton events is $\lesssim 0.02$ pb for $n\gtrsim 2$.

The cross section for gluino-initiated n jet$+$dilepton events $(1\leq n\leq 4)$ is shown in Fig. 9(a) as a function of $m_{\tilde{g}}$. The other supersymmetric (SUSY) parameters are fixed as before. Shown in Fig. 9(b) is the same cross section but for same-sign (SS) dileptons. We see that over almost the whole range of $m_{\tilde{g}}$, the SS cross section is just about half the total dilepton cross section for each event topology. This is consistent with the fact that the chargino decays are the dominant source of dileptons in gluino pair events. The wiggles in the curves reflect the statistical uncertainties in our Monte Carlo calculation coming from the fact that only $\sim 10^{-5}$ of the $\tilde{g}\tilde{g}$ events give rise to dilepton pairs that satisfy the cuts (10)–(12).

The SM n jet$+$dilepton cross sections from $t\bar{t}$ as well as vector-boson sources are shown in Table III for $m_t=75$ and 125 GeV. We see that the total signal is at least an order of magnitude below the t-quark background over the whole range of parameters. If $m_t\simeq M_W$ or $m_t\gtrsim 160$ GeV, however, the signal/background ratio for $n\geq 3$ shown in the figure can be larger than 1. Several 4 jets$+$dilepton pair events may be possible if an integrated luminosity of several hundred pb^{-1} is accumulated.

A better strategy[12] for isolating the signal is to focus on the same-sign (SS) dilepton events. Although this reduces the signal by about half, it virtually eliminates the SM backgrounds. SS dileptons, in principle, can result if one of the top quarks decays semileptonically and the other lepton comes from the semileptonic decay of the

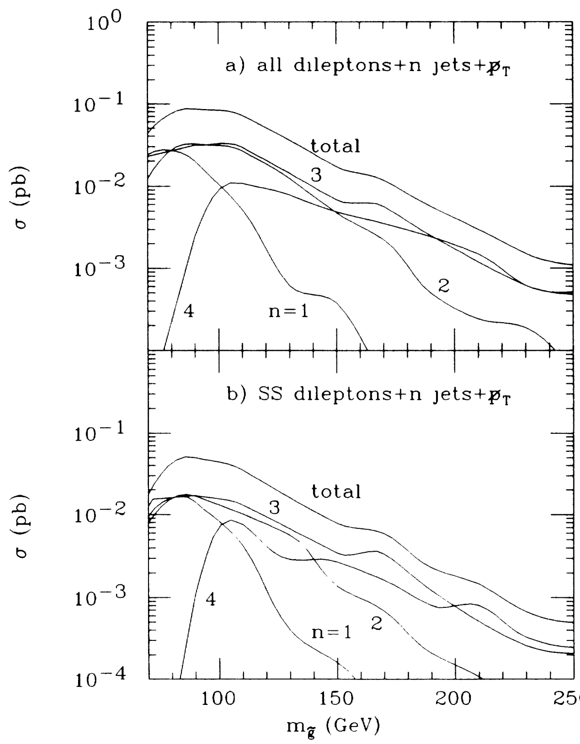

FIG. 9. Dilepton plus n jets$+\not{p}_T$ cross sections from gluino pair production at the Tevatron vs $m_{\tilde{g}}$ with cuts given in Sec. V and SUSY parameters as in Fig. 2. Standard-model backgrounds are given in Table III. For same-sign dileptons we find no SM backgrounds.

TABLE III. A tabulation of dominant backgrounds to opposite-sign dileptons$+n$ jets$+\not{p}_T$ gluino-pair signals, with the cuts of Sec. V.

n_j	$\tau\bar{\tau}$	WW	$t\bar{t}$ (75)	$t\bar{t}$ (125)	Total (75)	Total (125)
0	0.001	0.1	2	0.05	2	0.2
1	0.04	0.02	3	0.3	3	0.4
2	0.01	0.004	1	0.3	1	0.3
3	0.002		0.2	0.05	0.2	0.05
Total	0.05	0.1	6	1	6	1

daughter b quark (or antiquark) produced by the decay of the other t quark. In general, the second lepton is soft and usually part of a jet. We did not find any background to this class of events in agreement with the results of Barnett, Gunion, and Haber.[12]

These authors have also noted that $T^0\bar{T}^0$ mixing (here, T^0 is the bare top meson) could be a source of like-sign isolated dilepton$+n$-jet events within the SM. The cross section for such events is given by

$$\sigma_{SS}=\sigma(t\bar{t})[B(t\to l)]^2R \ , \qquad (13)$$

where R, the fraction of SS dilepton events, is given[26] by $2r/(1+r^2)$ with $r=x^2/(2+x^2)$ where $x=\Delta M/\Gamma$ is the standard mixing parameter and ΔM and Γ denote the mass difference and the average decay width of the two states. If we require this cross section to be $\gtrsim 10^{-2}$ pb corresponding to 1 event/year at the Tevatron design luminosity (and to a $\sim$150-GeV gluino in the signal), we find assuming $\sigma(t\bar{t})\lesssim 1$ nb (which is true for $m_t \geq 60$ GeV) that $x \gtrsim 10^{-2}$.

The expectation for x in the SM has recently been studied[27] at the Bombay Workshop on High Energy Physics Phenomenology for the top-meson system. Using the results of Ref. 28 the mixing parameter from the box diagram was shown to be smaller than 10^{-10} for the allowed range of Kobayashi-Muskawa parameters in the three-generation SM. It was further shown that x could be increased by at most a factor of 100 by introducing a fourth-generation quark with a large $V_{tb'}$ (this value is bounded by the observed $B_d^0\bar{B}_d^0$ mixing, of course). Finally, it was shown[27] that the increase of the mixing parameter due to charged scalars of a two-Higgs-doublet model was again at most a factor 100. It is, therefore, safe to conclude that the SS dilepton rate from top-meson mixing is completely negligible.

Barnett, Gunion, and Haber[12] have studied several distributions for this class of events. Based on these, they conclude that it may be possible to obtain an estimate of $m_{\tilde{g}}$ even at the Tevatron. It is, however, clear from Fig. 9 that the largest possible luminosities will be required to see this signal let alone deduce the gluino mass.

In summary, the t-quark decays swamp the total dilepton signal from gluinos for $m_t < 160$ GeV. Fortunately, almost half the gluino signal consists of like-sign dileptons for which we find no SM background. The cross section is, however *at most* a few $\times 10^{-2}$ pb so that it is extremely unlikely that the gluino will be discovered in this event topology. An observation of just a handful of these gold-plated events at the expected rate would, however, lead to a striking confirmation of the gluino signal in the $\not{p}_T$ channel and would also serve as conclusive evidence for the existence of the chargino. Finally, we note that the rates shown in Fig. 9 may be underestimated by as much as a factor of 2 if $m_{\tilde{q}} \sim 1$ TeV.

VI. SUMMARY

We have investigated the most promising signals from the production and subsequent decays of the gluinos of supersymmetry that may be accessible at the Fermilab Tevatron. As is well known[5,6,14,15] if the gluino is heavy enough, its decays (4) into the charginos ($\tilde{W}_-$) and neutralinos ($\tilde{Z}_2,\tilde{Z}_3,\tilde{Z}_4$) dominate the usually assumed decay (5) to the LSP. As can be seen from Fig. 1, the LSP mode may be suppressed to below 50% even for $m_{\tilde{g}}=80$ GeV and by even a larger factor for a heavier gluino. The inclusion of all the decays (4) in the analysis is, therefore, mandatory since the Tevatron is expected[8] to probe $m_{\tilde{g}} > 150$ GeV. In our analysis, we have incorporated all these decays as well as all the decays (6) of the daughter charginos and neutralinos as given by the minimal supergravity model.[11] A summary of the sparticle decay patterns is given in Sec. II.

In Sec. III we studied the signals resulting from the hadronic decays of gluinos for the experimental conditions of the CDF. The cross section for n jets$+\not{p}_T(>50$ GeV) events ($1\leq n \leq 7$) from gluinos is shown in Fig. 3. Also shown by dashed lines are the expected cross sections if the gluino could only decay into the LSP (in which case, apart from QCD radiation, $n\leq 4$). The SM rates for the same cuts are shown in Table I. It is important to note that the cascade decays reduce the $\not{p}_T$ cross section by a factor which may be larger than 3 for $m_{\tilde{g}}=150$ GeV and by even a larger amount for a heavier gluino. Also, while dijet events dominate for $m_{\tilde{g}}\sim 50-90$ GeV, four-jet topologies are dominant for $m_{\tilde{g}}>140$ GeV. On the other hand, if the gluino can only decay to the LSP trijet events dominate four-jet events even for $m_{\tilde{g}}=250$ GeV. We find that a gluino with a mass up to about 100 GeV can best be searched for in trijet$+\not{p}_T$ events; about 100 events should already be present in the current CDF data sample of $\sim$5 pb^{-1} of integrated luminosity, in contrast with just about 40 background events, if the gluino is in this mass range. Heavier gluinos may best be searched for in $n\geq 4$ jet topologies for which $\sigma\sim 2$ pb for $m_{\tilde{g}}=150$ GeV. The SM background has been estimated to have about the same cross section so that it may be possible to probe this mass range in the next run of the Tevatron. We note that the rates presented here are for $m_{\tilde{q}} = 2m_{\tilde{g}}$. The actual rates may be larger by as much as a factor 2 if the squark mass is about 1 TeV as can be seen from Fig. 4. Additional contributions from $\tilde{q}\tilde{q}$ and $\tilde{g}\tilde{q}$ production may also be present; we have not included these.

The leptonic decays of $\tilde{W}_i$ and $\tilde{Z}_i$ lead to the possibility of n jet$+m$ lepton$+\not{p}_T$ cross sections when the non-LSP decays of the gluino are incorporated. These are discussed in Secs. IV and V for $m=1$ and $m=2$, respectively. SM backgrounds to the single-lepton signal are large so that it seems unlikely that the gluino will ever be discovered in these events. We have shown, however, that by making judicious event selection (see Fig. 8) it may be possible to see the gluino signal if the top-quark decays to real W bosons.

Of particular interest is the same-sign[12] dilepton+jet signature coming from the decay of *both* gluinos into positive (or negative) charginos which then decay leptonically. This signal is characteristic of the Majorana nature of the gluino. The cross section for this class of events to which we have found no SM backgrounds is at most a few times 10^{-2} pb so that ~ 100 pb^{-1} of integrated luminosity is necessary to see this gold-plated gluino signature.

In summary, we have studied rates and distributions for various signals from the production and decays of gluinos at the Fermilab Tevatron, incorporating the decay patterns as given by the minimal supergravity model. Three signatures for the "cascade nature" of gluino decays are pointed out: events with ≥ 5 jets, single-lepton events, and dilepton events. An observation of the gluino signal in these event topologies is especially important since it would be indirect evidence for the existence of $\tilde{W}_i$ and $\tilde{Z}_i$. If the chargino is substantially heavier than 45–50 GeV, its strong production via gluino (or squark) decays may provide the first indication of its existence. In any case, signals should be present in each class of events if the discovery of the gluino is to be claimed.

ACKNOWLEDGMENTS

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