Phenomenology of Gluino Searches at the Tevatron

HOWARD E. HABER
Santa Cruz Institute for Particle Physics
University of California, Santa Cruz, CA 95064

Abstract

Present data indicates that the gluino (if it exists) must be heavier than about 95 GeV. During the next few years as the Tevatron integrated luminosity increases, gluino searches will be able to probe the mass range between 100 and 200 GeV. For masses in this range, a variety of gluino decay modes can provide viable signatures for gluino detection. Apart from the classic missing transverse energy signal, the detection of high transverse momentum like-sign dileptons may be the cleanest signature for gluino production. Other signatures such as the production of a hard photon in the gluino cascade decay may also play an important role in confirming the supersymmetric origin of events originating from gluino production and decay.

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1. The Gluino Mass Limit, circa 1992.

The Tevatron has recently completed its 1992-93 run and has delivered about 25 \(\text{pb}^{-1}\) of data to the CDF and D0 detectors. Next year, the Tevatron hopes to triple the accumulated luminosity of the 1992-93 run. With this large increase of data from the highest energy collider in the world, there is some hope that evidence for deviation from the Standard Model could soon be at hand. At this meeting on the status of supersymmetry in 1993, it is appropriate to reflect on the prospects for the discovery of supersymmetry at the Tevatron in the near future. Since squarks and gluinos have the largest production cross-sections at a hadron collider, it is these particles that have attracted the major attention of the two detector Collaborations in their searches for supersymmetry.

In supersymmetry searches at hadron colliders, two basic scenarios emerge. Gluinos and squarks are produced in pairs, so that possible final states are \(\tilde{g}\tilde{g}\), \(\tilde{q}\tilde{q}\) and \(\tilde{g}\tilde{q}\). If \(M_{\tilde{g}} < M_{\tilde{q}}\), then \(\tilde{g} \rightarrow \tilde{q}\tilde{q}\) (or \(\tilde{q}\tilde{g}\)), and one should first concentrate on the signatures of squark production at the Tevatron. Likewise, if \(M_{\tilde{q}} < M_{\tilde{g}}\), then \(\tilde{q} \rightarrow q\tilde{g}\), and it is appropriate to first focus attention on gluino production. Supersymmetric models do not yield a definitive statement as to which case is more likely to be realized in nature, although there may be a slight theoretical bias in favor of the lighter gluino. In this paper, I choose to consider the case of \(M_{\tilde{g}} < M_{\tilde{q}}\) and examine the phenomenology of gluino production and decay at the Tevatron.

During the past decade, many experiments have conducted searches for gluinos. The results of all such searches have been negative. From these negative searches, gluino mass limits have been obtained. In the literature, there has been some disagreement on the extracted gluino mass limits. A comprehensive discussion of these disagreements lies beyond the scope of this paper. Instead, I will state my personal opinions, and indicate how I draw my conclusions. A brief summary on the status of gluino searches is presented in Table 1.

Two main questions have been debated: (i) are very light gluinos allowed? and (ii) what is the maximum gluino mass ruled out by collider data? It is convenient to separate the discussion into two mass regimes: \(M_{\tilde{g}} < 3\ \text{GeV}\) and \(M_{\tilde{g}} > 3\ \text{GeV}\). The borderline between these two regions has been called the “light gluino window” in the literature. Recently, there has been a revival of interest in this region. A light gluino has been advocated in order to explain a possible inconsistency in the determination of \(\alpha_s\) by different techniques. Of course, experimental searches will be the final arbiter of the existence or non-existence of the light gluino window.

A variety of beam dump experiments and beam contamination searches rule out gluinos with \(M_{\tilde{g}} < 3\ \text{GeV}\), with some dependence on the gluino lifetime.

\[\text{†} \text{ Here, I do not distinguish between squarks and their antiparticles. On the other hand, gluinos are self-conjugate, a property that plays an important role in section 4.}\]
Perhaps the most definitive negative result is the non-existence of a pseudoscalar \( \tilde{g}\tilde{g} \) bound state (sometimes called the \( \eta_{\tilde{g}} \)). Such a state, if it existed, would be prominent in radiative quarkonium decay.\(^{10}\) Because gluinos are color octets, the decay rates for \( \psi \rightarrow \gamma \eta_{\tilde{g}} \) and \( \Upsilon \rightarrow \gamma \eta_{\tilde{g}} \) are enhanced by a color factor of 27/4 over the radiative decay into \( \gamma \eta_Q \), where \( \eta_Q \) is a pseudoscalar meson bound state of color-triplet quarks (\( e.g., \eta, \eta' \), and \( \eta_c \)). No such prominent pseudoscalar state is seen in the data. The published limits of the CUSB collaboration\(^{11}\) at CESR rules out gluino masses between 0.6 GeV and 2.2 GeV. Subsequent analysis of the CUSB data\(^3\) extended the upper mass limit to 2.6 GeV. Presumably, additional \( \Upsilon \) decay data now exists that could push the gluino mass bound above 3 GeV.

For gluino masses above 3 GeV, one must turn to the collider data. Gluino mass limits have been presented by the UA1\(^5\) and UA2\(^6\) Collaborations based on CERN pp Collider data and by the CDF Collaboration\(^7\) based on Tevatron data. These analyses assume that the gluino decays inside the detector with the emission of the lightest supersymmetric particle (LSP) which carries off undetected (“missing”) transverse energy. Only the UA1 data is sensitive to light gluino masses. The UA1 limits rule out gluinos in the range \( 4 \leq M_{\tilde{g}} \leq 53 \) GeV. This apparently leaves open the light gluino window. However, I believe that the UA1 limits are too conservative. In particular, the UA1 analysis did not take into account the mechanism \( gg \rightarrow \tilde{g}g\tilde{g} \) which is especially important for \( M_{\tilde{g}} < 5 \) GeV. In particular,
the kinematical configuration in which a hard gluon recoils against the two gluinos which are emitted in the same hemisphere can lead to substantial missing energy and pass the UA1 cuts. Barnett, Kane and I investigated this mechanism carefully and concluded that the UA1 data definitively ruled out gluino masses as light as 3 GeV. This essentially eliminates the possibility of the light gluino window.

The analyses of the UA2 and CDF Collaborations are not sensitive to the light gluino. However, their excluded mass regions overlap those of the UA1 analysis and therefore extend the UA1 gluino mass bound. The UA2 Collaboration concluded that $M_{\tilde{g}} < 79$ GeV. The CDF Collaboration has extended the gluino mass bound further; published results have been presented based on 4.3 pb$^{-1}$ of data from the 1989-91 Tevatron runs. In order to properly interpret the CDF data and extract gluino mass limits, one must incorporate all the allowed gluino decay patterns in the analysis. Typically, one assumes that the LSP is the lightest neutralino ($\tilde{\chi}_1^0$). Then, the simplest gluino decay is $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$, sometimes called “the direct decay to the LSP”. This is expected to be the dominant decay for light gluinos. For heavier gluinos, decays into heavier neutralinos and charginos $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_i^0$ and $\tilde{g} \rightarrow q\bar{q}'\tilde{\chi}_i^\pm$ become kinematically allowed, in which case, the branching ratio for the direct decay to the LSP drops significantly below 1. This is relevant for phenomenology since it is the direct decay into the LSP that produces the largest missing energy signature. When the gluino decays first into heavier neutralinos or charginos, these particles subsequently decay, eventually producing the LSP at the end of the decay chain. The end result is a gluino cascade decay that produces less missing energy than the direct decay to the LSP.

The CDF Collaboration has presented gluino mass limits under the assumption that $BR(\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0) = 1$. However, such mass limits are not very meaningful, since they correspond to a very unlikely choice of parameters for the supersymmetric model. For a more realistic example, consider the minimal supersymmetric extension of the Standard Model (MSSM), with gaugino Majorana mass parameters related according to the unification relation

$$M_i/M_j = \alpha_i/\alpha_j,$$

where the $i$ labels the gauge group, $\alpha_i \equiv g_i^2/4\pi$, and $g_1^2 \equiv (5/3)g'^2$. In this case,

\* There is an implicit assumption here that the gluino is heavier than $\tilde{\chi}_1^0$. Otherwise, the gluino would be the LSP and hence stable. Note that the CUSB limits quoted above also apply to stable gluinos. Beam contamination experiments then rule out stable gluinos for $M_{\tilde{g}} < 10$ GeV.\footnote{Heavier stable gluinos are disfavored for both theoretical and cosmological reasons, although this possibility cannot be completely excluded.}
the neutralino and chargino masses and mixing angles are determined by three parameters: the gluino mass \(M_{\tilde{g}}\), the ratio of Higgs vacuum expectation values \((\tan \beta)\) and the supersymmetric Higgs mass parameter \((\mu)\).\(^\text{12}\) Thus, for a given value of gluino mass, the parameters \(\mu\) and \(\tan \beta\) determine the relative branching ratios of the gluino into charginos and neutralinos [eq. (1.1)]. For gluino masses now being probed at the Tevatron, the probability of the cascade decays (in which the LSP is produced at the end of a multistep decay chain) is typically larger than the probability of direct decay to the LSP. Thus the missing energy signal is degraded and the true CDF gluino mass limit should be less than the quoted limit for \(BR(\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_0^1) = 1\). In ref. 7, the CDF Collaboration has included the effect of the cascade decays on their analysis. For one typical set of parameters, they deduced an upper gluino mass bound of about 95 GeV. This bound will surely be improved (by both the CDF and D0 Collaborations) once the 1992-93 Tevatron data is analyzed.

The bound \(M_{\tilde{g}} > 95\) GeV is the best bound presently available based on direct gluino searches. However, under the assumption of the unification of gaugino mass parameters [eq. (1.2)], the search for neutralinos and charginos at LEP can indirectly lead to a bound on \(M_{\tilde{g}}\). For example, in ref. 8, Hidaka concludes that \(M_{\tilde{g}} > 132\) GeV, based on the LEP limits on neutralino and chargino masses and including the effects of cascade decays on the CDF gluino search analysis mentioned above.\(^\text{†}\)

\(^\text{†}\) To conclude this introduction, my personal opinion is that based on current published data, \(M_{\tilde{g}} \gtrsim 125\) GeV, with no open light gluino window. Looking to the near future, the Tevatron runs in 1992-93 and 1993-94 will yield about 25 pb\(^{-1}\) and 75 pb\(^{-1}\) per detector, and should increase the gluino mass sensitivity to about 200 GeV. The purpose of this talk is to indicate some of the phenomenological methods available to achieve this sensitivity. In section 2, I present a brief review of the theory of gluino cascade decays. For gluino masses that can be detected at the Tevatron, there are three important gluino decays: (i) the direct decay to the LSP \((\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_0^1)\), (ii) \(\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_2^0\), and (iii) \(\tilde{g} \rightarrow q\bar{q}'\tilde{\chi}_1^\pm\). In case (ii), a viable signature results if \(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\gamma\); this is the subject of section 3. In case (iii), note that the Majorana nature of the gluino\(^\ddagger\) leads to equal probability for producing either sign chargino. Thus, if the chargino decays semi-leptonically, \(\tilde{g}\tilde{g}\) events can lead to like-sign dileptons in the final state. This is the subject of section 4.

\(^\ddagger\) The inferred gluino mass limit of ref. 8 was based in part on a preliminary CDF analysis of their 1989–91 data, and should probably be reduced slightly in light of the published CDF results. Note that the LEP limits on chargino and neutralino masses are basically at their kinematic limits and hence will not change with further running at \(\sqrt{s} = m_Z\).

\(^\ddagger\) Here, I am using a broader definition of Majorana to include neutral particles that transform under real representations of the underlying Standard Model gauge group.
2. The Theory of Gluino Cascade Decays

At the Tevatron, the dominant production mechanism for gluinos is $gg \to \tilde{g}\tilde{g}$ via s-channel gluon and $t$- and $u$-channel gluino exchange. The $\tilde{g}\tilde{g}$ coupling follows from QCD gauge invariance, so that the gluino cross-section depends on only one unknown parameter—the gluino mass. Gluinos can also be produced in $q\bar{q}$ annihilation via squark-exchange. However, this produces only a minor change in the overall gluino cross-section. Thus, gluino phenomenology depends on the gluino mass and the parameters that govern the gluino decay branching ratios. The most important gluino decay modes are tree-level three body decays into a neutralino or chargino and a $q\bar{q}$ pair [eq. (1.1)]. With the exception of $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$, the neutralino or chargino in the final state will decay into a lighter neutralino or chargino and so on until the LSP (assumed to be $\tilde{\chi}_1^0$) is produced. Branching ratios for the gluino cascade decays depend on various supersymmetric parameters. For convenience, I list below the parameters of the MSSM:

1. The gaugino Majorana mass parameters ($M_1$, $M_2$ and $M_3$).
2. The supersymmetric Higgs mass parameter, $\mu$.
3. The ratio of Higgs vacuum expectation values, $\tan \beta$.
4. The mass of the CP-odd Higgs scalar, $m_{A^0}$.
5. Diagonal ($\tilde{f}_L\tilde{f}_L$ and $\tilde{f}_R\tilde{f}_R$) squark and slepton mass parameters.
6. Off-diagonal ($\tilde{f}_L\tilde{f}_R$) squark and slepton mass parameters (which depend on $\mu$, $\tan \beta$ and various “$A$”-parameters.)

The gluino mass is given by $M_{\tilde{g}} = |M_3|$, and the chargino and neutralino masses and mixing angles are determined by $M_1$, $M_2$, $\mu$ and $\tan \beta$. The Higgs sector parameters are fixed by $\tan \beta$ and $m_{A^0}$. This is relevant to the considerations here since neutralinos and charginos can decay into final states containing Higgs bosons. Finally, gluino production rates and branching ratios depend very weakly on squark masses. (Here, I assume that $M_{\tilde{g}} < M_{\tilde{q}}$ and $\tilde{g}\tilde{g}$ and $q\bar{q}$ production rates can be neglected.) As mentioned above, the $\tilde{g}\tilde{g}$ cross-section is dominated by gluon and gluino exchange. The gluino decays via squark exchange, but this just means that the squark mass determines the overall normalization of the gluino decay width. To the extent that squarks are roughly degenerate in mass, gluino branching ratios will be independent of the squark mass.\footnote{\textsf{\textsuperscript{\S}} The coupling of gluinos to $q\bar{q}$ is independent of the flavor of $q$. Moreover, with the exception of the top-squark, all squarks are expected to be roughly degenerate in mass. Interesting effects could arise if top-squark mixing effects are important. However, the decay $\tilde{g} \to t\tilde{\chi}_1^0$ is not kinematically allowed for gluinos accessible to Tevatron searches. Thus, it is probably safe to ignore the variation of squark masses.} For heavy gluinos relevant for Tevatron searches, the gluino decays essentially instantaneously (with no visible gap between production and subsequent decay). In considering the subsequent
decay of charginos and neutralinos in the gluino decay chain, all the supersymmetric parameters enter to some extent. For example, charginos and neutralinos produced in gluino decays at the Tevatron will typically decay via squark, slepton, W or Z exchange into three-body final states. However, even in this case, the sensitivity to squark and slepton parameters is not significant, since squark and slepton masses almost certainly lie above $m_Z$.

Two critical assumptions underlie the analysis presented in this paper. First, as discussed in section 1, I shall assume that the gluino is lighter than all squark masses (with the possible exception of the top-squark). As noted above, once I assume that $M_{\tilde{g}} < M_{\tilde{q}}$, the precise value of $M_{\tilde{q}}$ is not important. Second, I shall impose the grand unification relation which states that the gaugino mass parameters $M_1$, $M_2$ and $M_3$ are all equal at some very large grand unification (or Planck) scale. I then use one-loop renormalization group evolution to determine the value of the $M_i$ at the electroweak scale. One finds that the scaling of $M_i$ is proportional to the squared coupling constants $\alpha_i$ [eq. (1.2)]. As a result, the low-energy values of $M_1$ and $M_2$ can be expressed in terms of the gluino mass

$$M_2 = (g^2/g_s^2)M_{\tilde{g}} \simeq 0.285M_{\tilde{g}}, \quad M_1 = (5g'^2/3g^2)M_2 \simeq 0.483M_2. \quad (2.1)$$

This relation underlies nearly all phenomenological analyses of the MSSM that appear in the literature. Perhaps it is time to begin to consider some of the phenomenological consequences of the violation of eq. (2.1). However, I will not pursue this alternative here.

Barnett, Gunion and I have studied the branching ratios for the gluino, neutralino and chargino as a function of the supersymmetric parameters. (See also the results of ref. 17.) Below, I summarize some of the highlights of our investigation.

1. The gluino branching ratio for the direct decay to the LSP is small over a substantial portion of parameter space. This conclusion relies on the relation among the gaugino mass parameters [eq. (2.1)]. In particular, $BR(\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0_1) \leq 0.14$ for $M_{\tilde{g}} \gtrsim 500$ GeV. For gluino masses accessible to future Tevatron searches, this branching ratio may be somewhat larger (depending on the values of $\mu$ and $\tan \beta$), although it is less than 50% in all but a narrow region of parameter space, as shown in fig. 1. Thus, most gluino decays will be cascade decays, which dilute the famous missing transverse energy signature.

2. The dominant gluino decay mode [except for regions of parameter space where $\tan \beta$ is near 1 and $|\mu| \lesssim O(m_Z)$] is $\tilde{g} \rightarrow \tilde{\chi}^\pm_1 + X$ where X is either $ud$ or $cs$ (or the charge conjugate pair, depending on the sign of $\tilde{\chi}^\mp_1$). For example, if $\tan \beta = 4$ and $M_{\tilde{g}} = 120$ GeV, the sum of the branching ratios for gluino decay into $\tilde{\chi}^\pm_1$ is approximately 58% (with very weak dependence on $\mu$; see fig. 1).
Moreover, because the gluino is a Majorana fermion,
\[ \Gamma(\tilde{g} \rightarrow \tilde{u}d\tilde{x}_1^+) = \Gamma(\tilde{g} \rightarrow \tilde{u}d\tilde{x}_1^-). \] (2.2)

Thus, in $\tilde{g}\tilde{g}$ production, like-sign charginos can be produced, which can lead to like-sign dileptons if both charginos decay semi-leptonically. This is the subject of section 4.

3. The decay $\tilde{g} \rightarrow q\bar{q}\tilde{x}_2^0$ is competitive with the direct decay into the LSP. It is the second most important gluino decay mode over a substantial range of MSSM parameter space.

The phenomenology of gluino cascade decays will depend in detail on the neutralino and chargino branching ratios. Since we are interested here in gluinos in the mass range between 100 and 200 GeV, the corresponding masses of $\tilde{x}_1^\pm$ and $\tilde{x}_2^0$ will be such that tree-level two body decays $\tilde{x}_1^\pm \rightarrow W^\pm \tilde{x}_1^0$ and $\tilde{x}_2^0 \rightarrow \tilde{x}_1^0 Z$ are kinematically forbidden. If no other tree-level two body decays are possible, then the dominant decays of $\tilde{x}_1^\pm$ and $\tilde{x}_2^0$ will be: $\tilde{x}_1^\pm \rightarrow \tilde{x}_1^0 f \bar{f}'$ and $\tilde{x}_2^0 \rightarrow \tilde{x}_1^0 f \bar{f}$, where $f$ is either a quark or lepton. Although this is certainly the most likely situation, it is important to consider two alternative cases. If neutral Higgs bosons (the CP-even $h^0$ and the CP-odd $A^0$) are sufficiently light, then the two-body decays $\tilde{x}_2^0 \rightarrow \tilde{x}_1^0 h^0$ and $\tilde{x}_2^0 \rightarrow \tilde{x}_1^0 A^0$ could be kinematically allowed. For example, ref. 16 argued that a significant region of parameter space exists in which $\tilde{x}_2^0 \rightarrow \tilde{x}_1^0 h^0$ is the dominant decay mode. Since that analysis, two new pieces of information suggest that the Higgs decay mode of $\tilde{x}_2^0$ will not be significant at the Tevatron gluino search. First, the LEP Higgs search implies that $m_{h^0} \gtrsim 60$ GeV.19 Second, radiative corrections can significantly increase the theoretical expectation for $m_{h^0}$.20 As a result, the “3-body decay region” discussed in ref. 16 expands substantially at the expense of the “light-Higgs region”. Finally, although I have assumed in this paper that squarks are heavier than gluinos, it could happen that sleptons are significantly lighter than the squarks (as suggested by renormalization group evolution of low-energy supergravity models). If the sleptons are lighter than the lightest chargino or neutralino, then two-body decays such as $\tilde{x}_1^\pm \rightarrow \ell \bar{\nu}$, $\tilde{x}_1^\pm \rightarrow \hat{\ell} \nu$, $\tilde{x}_2^0 \rightarrow \hat{\ell} \ell$, and/or $\tilde{x}_2^0 \rightarrow \nu \bar{\nu}$ may be kinematically allowed. We shall see in section 4 that if these two-body chargino decay modes are present, then the like-sign dilepton signal in $\tilde{g}\tilde{g}$ events is significantly enhanced.

Finally, there is one more two-body decay mode of potential significance—the radiative decay $\tilde{x}_2^0 \rightarrow \tilde{x}_1^0 \gamma$.22 This is not a tree-level process; it occurs only at one-loop. Nevertheless, it turns out that the radiative decay mode can compete with the three-body modes (and in some cases it can be the dominant mode) in certain parameter regimes. This is the subject of section 3.

We have seen above that the branching ratio for $\tilde{g} \rightarrow q\bar{q}\tilde{x}_1^0$ is expected to be small (less than 50%, and more likely closer to about 20%). As a result, the missing
transverse energy signal is degraded relative to the case of a 100% branching ratio for the direct decay to the LSP. Nevertheless, the missing transverse energy signature will still be important. For example, \( \tilde{g}\tilde{g} \) events in which one \( \tilde{g} \) decays directly to the LSP and the second \( \tilde{g} \) decays arbitrarily will still produce a significant missing transverse energy signal. However, in order to maximize the efficiency of the Tevatron gluino search, other gluino signatures should be examined. In particular, we noted above that for \( 100 < M_{\tilde{g}} < 200 \) GeV,

\[
BR(\tilde{g} \rightarrow \tilde{\chi}_1^\pm q\bar{q}) > BR(\tilde{g} \rightarrow \tilde{\chi}_2^0 q\bar{q}) > BR(\tilde{g} \rightarrow \tilde{\chi}_1^0 q\bar{q})
\] (2.3)

over nearly all of the relevant MSSM parameter space. Thus, it is important to examine distinctive gluino signatures arising from the \( \tilde{g} \) decay to \( \tilde{\chi}_1^\pm \) and \( \tilde{\chi}_2^0 \).

3. Hard Photons in Gluino Cascade Decays

Consider \( \tilde{g}\tilde{g} \) events in which one gluino decays to \( \tilde{\chi}_2^0 \) via \( \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_2^0 \), while the decay mode of the second gluino is arbitrary. In this section, I shall consider the case where \( \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma \). Such events are characterized by the emission of a hard photon, one or more large \( E_T \) jets, and significant missing \( E_T \). Events of this type are already being searched for at the Tevatron. In this section, I shall present the preliminary results of a calculation to estimate the fraction of \( \tilde{g}\tilde{g} \) events with a hard photon.

The branching ratio for gluino decay into \( \tilde{\chi}_2^0 \) is typically between 20% and 30% for gluino masses of interest to the Tevatron search. We then need to compute \( BR(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma) \) as a function of the MSSM parameters. The complete amplitude for the one-loop process \( \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma \) has been computed in ref. 22. To evaluate the branching ratio, one must also compute the sum of all tree-level decays of the \( \tilde{\chi}_2^0 \). It is clear that any kinematically allowed tree-level \( \tilde{\chi}_2^0 \) decay into two-body final states would dominate the one-loop radiative decay (as well as tree-level decays into three-body final states). For the range of neutralino masses relevant for the Tevatron gluino search, the only possible allowed two-body (tree-level) decays are \( \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h^0 \) and \( \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 A^0 \). However, as argued in section 2, if one takes into account the LEP Higgs mass limits and the results of the one-loop corrected MSSM Higgs masses, one would conclude that the tree-level \( \tilde{\chi}_2^0 \) decays to \( h^0 \) and/or \( A^0 \) are likely to be present only over a small region of parameter space. Henceforth, I shall assume that these decays are kinematically forbidden. In this case, the three-body (tree-level) \( \tilde{\chi}_2^0 \) decay modes are dominant. However, I shall now show that the radiative decay \( \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma \) is competitive over a rather large region of parameter space of interest to the Tevatron gluino search.
In figs. 2–4, I have plotted $BR(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma)$ as a function of MSSM parameters for a variety of gluino masses. These figures show that in the region of negative $\mu^\star$, the typical value of $BR(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma)$ is 10%. This means that in the Tevatron gluino search, approximately 5% of all $\tilde{g}\tilde{g}$ events should contain a hard photon originating from $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$. It remains to be seen whether the reducible backgrounds can be removed (e.g., events in which a neutral jet or leading $\pi^0$ is misidentified as a photon) thereby leaving a viable signal. I suspect that the gluino will not be discovered via the radiative $\tilde{\chi}_2^0$ decay. However, if evidence for the gluino is uncovered in other channels, the detection of hard photon events could help to confirm the gluino interpretation of the other signals as well as pinpoint some of the MSSM parameters.

4. Discovering Gluinos with Like-Sign Di-Leptons

In this section, I shall focus on the striking experimental signature of two isolated leptons which can arise from gluino pair production. Half of the events of this type will have leptons with the same sign of electric charge. This signature, which is analogous to the opposite-sign lepton signal for the top quark, may yield sensitivity much superior to the missing-energy gluino signature at the Tevatron, depending on the parameters of the supersymmetric model. The results of this section are based on work in collaboration with R.M. Barnett and J.F. Gunion (see also ref. 27 for an earlier version of this work). Complementary work that also considered the like-sign dilepton signature can be found in refs. 18 and 28–33.

As discussed in section 2, for gluino masses accessible to the Tevatron search, the dominant gluino decay mode is $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^\pm$, over a large range of supersymmetric parameter space. Leptons can result from decays such as $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0 \rightarrow \ell^\pm \nu\tilde{\chi}_1^0$, where the $W^\pm$ is either on-shell (if kinematics allow) or off-shell. If the sleptons are lighter than the chargino, then the two-body decays $\tilde{\chi}_1^\pm \rightarrow \tilde{\ell}^\pm \nu \rightarrow \ell^\pm \nu\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm \rightarrow \tilde{\nu}_\ell \rightarrow \ell^\pm \nu\tilde{\chi}_1^0$ are allowed and may dominate. Since the gluino is a Majorana fermion, it has the distinctive property of decaying with equal probability into fermions and antifermions. Thus, an excellent signature for pair production of gluinos results from events in which both gluinos decay to a chargino of the same sign, yielding like-sign dileptons ($\ell^+\ell^+$ or $\ell^-\ell^-$) in the final state. The probability for the production of like-sign and opposite-sign leptons is equal, and the characteristics of the two classes of final states are identical. Observation of this distinctive result would be extremely helpful in identifying the origin of the events.

* The LEP limits on neutralino and chargino masses tend to rule out regions of $-40 \text{ GeV} \lesssim \mu \lesssim 80 \text{ GeV}$ (with some variation depending on $M_2$ and $\tan \beta$).\textsuperscript{19}
To be specific, we have taken the branching ratio for gluino decay to the lightest chargino to be \( BR(\tilde{g} \rightarrow q\bar{q}^\pm\tilde{\chi}^\pm_{1}) = 0.58 \), a result which holds to good accuracy for all \(|\mu| > M_3/3, m_Z| \).\(^{15}\) Moreover, this value for the branching ratio is approximately valid for nearly all MSSM parameters of relevance to the Tevatron gluino search.\(^\dagger\) If the \( \tilde{\ell} \) and \( \tilde{\nu} \) are heavier than the chargino, the chargino decays dominantly into the LSP plus a real (or virtual) \( W^\pm \) which then decays 22% of the time into electrons and muons. Thus the branching ratio for the decay chain \( \tilde{g} \rightarrow q\bar{q}\ell^\pm\nu_{\tilde{\chi}^0_1} \) is likely to be as large as 13%, with equal probability to produce a lepton of either sign. (For simplicity, the \( \tau \)-lepton will be neglected from our considerations.) Since gluinos are produced in pairs, the number of dilepton final states resulting from the decay of the two gluinos would be about 1.6% of all \( \tilde{g}\tilde{g} \) events, of which half would have a pair of like-sign leptons. However, if \( M_{\tilde{\ell}} \) and/or \( M_{\tilde{\nu}} < M_{\tilde{\chi}^\pm_1} \), and \( M_{\tilde{\chi}^\pm_1} < m_W + M_{\tilde{\chi}^0_1} \), then the two-body decays of the \( \tilde{\chi}^\pm_1 \) to \( \tilde{\ell}\nu \) and/or \( \tilde{\nu}\ell \) will have approximately 100% branching ratio into leptonic final states (including the \( \tau \)-lepton). If we neglect \( \tau \)-leptons, we find \( BR(\tilde{g} \rightarrow q\bar{q}\ell^\pm\nu_{\tilde{\chi}^0_1}) \) close to 40%. A remarkable 15% of all \( \tilde{g}\tilde{g} \) events would yield a dilepton final state.

Thus, we propose that the Tevatron search for events with hadronic jets (two from each gluino), missing energy due to the LSP and neutrinos in the final state, and a dilepton pair which can come in one of the following like-sign combinations: \( e^\pm e^\pm, \mu^\pm \mu^\pm, \mu^\pm \mu^\pm \), and the corresponding opposite-sign combinations. The events would be very similar to those arising from \( t\bar{t} \) production in which the leptons come from primary decays of the \( t \) and \( \bar{t} \). Thus, distinguishing the source of opposite-sign events might be difficult. Because the efficiency for tagging \( b \)-jets is low and because some fraction of \( \tilde{g}\tilde{g} \) events will contain \( b \)-jets from a hard radiated gluon, \( b \)-jets may not be a useful tool for separating \( t\bar{t} \) from \( \tilde{g}\tilde{g} \) events. For this reason we will focus on like-sign dilepton final states for which \( t\bar{t} \) production yields a background only through \( \tilde{\ell} \rightarrow \tilde{b}\ell^{-}\nu \) and \( t \rightarrow bX, b \rightarrow c\ell^{-}\nu \) (or the corresponding charge-conjugated decay chain). This background would be quite small since the lepton from the \( b \) decay would very rarely be isolated.

We have evaluated the rates for the dilepton signal in gluino pair production at the Tevatron. In order to roughly account for realistic experimental conditions, we have employed a parton-level Monte Carlo, which included resolution smearing but no fragmentation, to model the \( \tilde{g}\tilde{g} \) events.\(^\ddagger\) The surprisingly large potential for gluino discovery at the Tevatron becomes apparent by giving the number of dilepton (opposite- plus like-sign) events obtained in a 25 pb\(^{-1}\) year. For the case

\(^\dagger\) For example, when \( M_3 \lesssim 200 \text{ GeV} \) and \( \tan \beta \gtrsim 4 \), \( BR(\tilde{g} \rightarrow q\bar{q}^\pm\tilde{\chi}^\pm_{1}) \) varies between about 45% and 65% as \( \mu \) is varied.

\(^\ddagger\) A description of a similar program to analyze the characteristics of supersymmetric events at the CERN \( pp \) collider can be found in ref. 4.
Table 2. Number of $\ell^+\ell^+$ plus $\ell^\pm e^\mp$ events after lepton cuts for various $M_{\tilde{g}}$ values at the Tevatron with an integrated luminosity of 25 pb$^{-1}$. The various decay modes of the $\tilde{\chi}_1^\pm$ are indicated by $W (W_{\tilde{\chi}_1^0})$, $\ell (\ell\nu)$, $\tilde{\nu} (\tilde{\nu}\ell)$. These rates assume the branching ratios quoted earlier (which are, in fact, typical over a wide range of parameters).

| Mode   | $W$ | $W$ | $\tilde{\ell}$ | $\tilde{\nu}$ | $\tilde{\nu}$ | $\tilde{\ell}$ | $\tilde{\ell}$ | $\tilde{\nu}$ | $\tilde{\nu}$ | $\tilde{\ell}$ | $\tilde{\ell}$ | $\tilde{\nu}$ | $\tilde{\nu}$ | $\tilde{\ell}$ | $\tilde{\ell}$ | $\tilde{\nu}$ | $\tilde{\nu}$ | $\tilde{\ell}$ | $\tilde{\ell}$ | $\tilde{\nu}$ | $\tilde{\nu}$ |
|--------|-----|-----|----------------|---------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| $M(\tilde{g})$ | 140 | 140 | 140 | 160 | 160 | 180 | 180 | 180 | 180 | 200 | 200 | 140 | 140 | 160 | 160 | 180 | 180 | 180 | 180 | 200 | 200 |
| $M(\tilde{\chi}_1^\pm)$ | 80 | 60 | 45 | 60 | 80 | 80 | 80 | 80 | 45 | 80 | 80 | 80 | 60 | 40 | 40 | 60 | 50 | 75 | 40 | 40 | 60 | 75 | 40 |
| $M(\ell$ or $\tilde{\nu}$) | – | – | – | 40 | 70 | 50 | 75 | 55 | 40 | 40 | 60 | 50 | 75 | 40 | 40 | 60 | 50 | 75 | 40 | 40 | 60 | 75 | 40 |
| Events | 9 | 6 | 3 | 22 | 9 | 12 | 30 | 22 | 9 | 28 | 20 | 7 | 15 | 15 |

where the $\tilde{\chi}_1^\pm$ decays to $\tilde{\ell}\nu$ or $\ell\tilde{\nu}$, the net branching ratio of 15% quoted above yields roughly 1440, 476, 183, 79, 37, and 18 dilepton events (before cuts) for gluino masses of 100, 120, 140, 160, 180, and 200 GeV, respectively. Dilepton rates originating from $\tilde{\chi}_1^\pm \to W^{(*)}\tilde{\chi}_1^0$ decays are a factor of roughly 9 smaller.

To estimate the rates for detectable dilepton events at the Tevatron, we assume a trigger which requires that the leading (secondary) lepton has $E_T > 15 \ (10)$ GeV. In addition, we require $|\eta| < 2.5$ and isolation for both leptons. Associated hadronic jets are not required. The probability that events pass these cuts depends in detail upon the masses of the particles involved in the decay chains, but is roughly 50% for much of parameter space. We have explored a range of supersymmetric parameters for which the mass $M_{\tilde{\chi}_1^\pm}$ varies between about 45 GeV (its current lower bound from LEP data$^{34}$) and 80 GeV, while letting the gluino mass vary between 100 and 200 GeV. In the corresponding range of MSSM parameter space, the mass of the LSP ($\tilde{\chi}_1^0$) is approximately given by $M_{\tilde{g}}/6$.

For $\tilde{\chi}_1^\pm \to W^{\pm}\tilde{\chi}_1^0$, the 1.6% net branching ratio quoted earlier yields between 70 and 1 dilepton events (of which half are like-sign) per 25 pb$^{-1}$ at the Tevatron for $M_{\tilde{g}}$ between 100 and 160 GeV. In contrast, if the $\tilde{\chi}_1^\pm$ decays to $\ell\nu$ and/or $\ell\tilde{\nu}$, the larger 15% net branching ratio can result in up to 1100 (15) dilepton events for $M_{\tilde{g}} = 100 (200)$ GeV, depending on the decay mode and the various masses.

To illustrate, we present in Table 2 the dilepton event rates (for an integrated luminosity of $L = 25 \text{ pb}^{-1}$) for various cases which yield $\lesssim 30$ events. For comparison, with our cuts, 12 events are expected from $t\bar{t}$ production for $m_t = 140$ GeV, but all of these have opposite-sign leptons. Thus, for comparable gluino and top quark masses, the additional requirement of two isolated like-sign leptons would

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§ An isolated lepton is defined to be one that is separated by at least 0.3 units in $\Delta R \equiv [(\Delta \eta)^2 + (\Delta \phi)^2]^{1/2}$ from any parton (or “merged parton jet” if two or more partons are within 0.7 units in $\Delta R$ of each other).
reduce the top quark rate to a level far below that from gluinos. However, a top quark significantly lighter than the gluino might require that additional cuts be made to separate the two signals.

The event rate depends strongly on the lepton cuts. The lepton spectrum itself is quite sensitive to decay modes and decay product masses. For the chargino three-body decay to $\tilde{\chi}_1^0(\ell\nu)$ via a virtual $W$, the lepton spectrum depends primarily on $M_{\tilde{\chi}_1^\pm} - M_{\tilde{\chi}_1^0}$. For chargino decays to $\tilde{\ell}\nu$ ($\tilde{\nu}\ell$), the spectrum is essentially determined by $M_{\tilde{\ell}} - M_{\tilde{\chi}_1^0}$ ($M_{\tilde{\chi}_1^\pm} - M_{\tilde{\nu}}$). Because of the current experimental limit of $M_{\tilde{\ell}} > 44$ GeV, most leptons from $\tilde{\ell}$ decay pass our cuts for the $M_{\tilde{\chi}_1^0}$ values employed. Thus, even for the relatively large gluino masses of 160 and 180 GeV, the $\tilde{\ell}\nu$ decay event rates illustrated are large enough to be in possible conflict with observed rates at the Tevatron. In contrast, as illustrated in Table 2, the event rate associated with $\tilde{\chi}_1^\pm \to \ell\tilde{\nu}$ decays could be very small since small values of $M_{\tilde{\chi}_1^\pm} - M_{\tilde{\nu}}$ are possible, leading to a soft lepton that is unlikely to pass our cuts. However, even for $M_{\tilde{\ell}} = 180$ GeV, if the $\tilde{\nu}$ mass is not close to $M_{\tilde{\chi}_1^\pm}$ then the event rate for the $\ell\tilde{\nu}$ mode is large.

Thus, if very few or no like-sign dilepton events are found after accumulating $L = 25$ pb$^{-1}$, then improved limits on the gluino mass (as a function of other MSSM parameters) will be attainable. If $\tilde{\chi}_1^\pm \to W^{\pm*}\tilde{\chi}_1^0$ is the dominant decay, a modest improvement of $M_{\tilde{\ell}} > 120$ GeV is possible, based on the like-sign dilepton search. In contrast, if $\ell\tilde{\nu}$ or $\tilde{\ell}\nu$ decays of the $\tilde{\chi}_1^\pm$ are dominant and the $\ell$ spectra are not suppressed by a small mass difference, then limits of order $M_{\tilde{\ell}} > 200$ GeV will be obtained over the large region of parameter space for which $BR(\tilde{g} \to q\bar{q}'\tilde{\chi}_1^\pm)$ is substantial.

Assuming that one has succeeded in isolating gluino candidates, it is important to ask if one can estimate the mass of the gluino, and the masses of the decay products. If we define a hadronic jet as having $E_T > 15$ GeV and pseudorapidity $|\eta| < 2.5$, the gluino pair events will typically have between 2 and 4 jets. The $E_T$ spectrum of the jets is completely determined by $M_{\tilde{\ell}} - M_{\tilde{\chi}_1^\pm}$. For the extreme case of $M_{\tilde{\ell}} = 100$ GeV and $M_{\tilde{\chi}_1^\pm} = 80$ GeV, all jets are too soft ($E_T < 15$ GeV) for identification. In contrast, the missing $E_T$ spectrum is not strongly dependent on the mass splittings or chargino decay modes, at least for gluino and chargino masses in the ranges considered here, and is centered at about 50 GeV. We have performed detailed studies and find that the most useful distributions for mass determinations are $E_T^{\ell\max}$, the $E_T$ of the most energetic lepton and $E_T^{j\max}$, the transverse energy of the jet with largest $E_T$. For any given decay chain, these can be used to estimate the mass differences, and the overall event rate can then be used to determine the absolute mass scale, provided statistics are adequate. However, with $L = 25$ pb$^{-1}$, event rates for $W$-mediated decays of the $\tilde{\chi}_1^\pm$ at
the Tevatron are inadequate. For $\tilde{\nu}$ and/or $\tilde{\ell}$ decays, predicted event rates are such that $\pm 25$ GeV would be achievable for $M_{\tilde{g}} \lesssim 160$ GeV. But, as already noted, such large event rates are probably inconsistent with current observations at the Tevatron. Scenarios consistent with current Tevatron rates would require $L \gtrsim 100 \text{ pb}^{-1}$ to achieve a $\pm 25$ GeV estimate of $M_{\tilde{g}}$. In this regard, it is important to note that knowledge of the relative importance of the $\tilde{\nu} \tilde{\ell}$ decays of the $\tilde{\chi}_1^\pm$ is, in principle, not required in order to estimate $M_{\tilde{g}}$. The $E_T^{\ell \text{max}}$ spectrum will allow an estimate of how many events per produced gluino have passed the lepton cuts, and the overall event rate will then allow an estimate of $M_{\tilde{g}}$. The $E_T^{j \text{max}}$ spectrum would then allow us to estimate $M_{\tilde{\chi}_1^\pm}$. Of course, if $M_{\tilde{\chi}_1^\pm}$ is known from other sources (e.g. LEP-II), $M_{\tilde{g}}$ can be estimated from the $E_T^{j \text{max}}$ spectrum alone, without relying on the absolute event rate predictions which will have substantial systematic uncertainties.

The like-sign signature for $g\tilde{g}$ production provides a powerful tool, both for discovering evidence for supersymmetry and for estimating the gluino mass. It is the Majorana nature of the gluino that yields this striking signature. At the Tevatron collider, favorable assumptions concerning gluino cascade decay branching fractions, gluino production could yield as many as 1100 dilepton events (after significant lepton cuts) in the current 25 pb$^{-1}$ run, of which half would be like-sign. Since large numbers of events are not seen, many new constraints on the masses of the $\tilde{g}$, $\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^0$, $\tilde{\ell}$ and $\tilde{\nu}$ will be obtained. If the handful of dilepton events currently observed at the Tevatron were due to $g\tilde{g}$ production, an integrated luminosity of at least $L = 100 \text{ pb}^{-1}$ would be required to obtain a $\pm 15\%$ estimate of the gluino mass.

5. Conclusions

The Tevatron is expected to have accumulated nearly 100 pb$^{-1}$ of data by the end of the 1993-94 run. The data that will be collected by the CDF and D0 Collaborations will be sensitive to gluino masses up to 200 GeV. The detection of a gluino signal may occur through a variety of techniques. In addition to the classic missing transverse energy signal, experimenters should search for isolated like-sign di-leptons and isolated hard photons in events with jets and missing energy. Detection of a positive signal in at least two of these three channels could be critical for confirming a gluino interpretation of the detected events. In addition, with a signal in more than one channel, one can begin to zero in on specific values of some of the MSSM parameters.

In the absence of any of the signals mentioned above, one would conclude that gluinos (and probably squarks as well) are too heavy to be produced at the Tevatron in the near future. Although a modest improvement of gluino mass limits
could be achieved with the upgraded Fermilab main injector (perhaps, detectable gluinos with \( M_{\tilde{g}} < 300 \) GeV for \( L = 1000 \) pb\(^{-1}\)), one will need the services of a supercollider (either LHC or SSC) to definitively establish or rule out the existence of the gluino of low-energy supersymmetry.

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FIGURE CAPTIONS

1) The branching ratios for $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_0^i$ and $\tilde{g} \rightarrow q\bar{q}'\tilde{\chi}_j^\pm$ as a function of $\mu$ for $M_{\tilde{g}} = 120$ and $300$ GeV and $\tan\beta = 1.5$ and $4$. Sections of the curves that are not plotted correspond to parameter choices that yield $M_{\tilde{\chi}_i^\pm} < m_Z/2$. Taken from Ref. 15.

2) $BR(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\gamma)$ as a function of the MSSM parameter $\mu$, for $\tan\beta = 2$. The three curves correspond to different choices of gluino masses as indicated on the figure.

3) $BR(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\gamma)$ as a function of the MSSM parameter $\mu$, for $\tan\beta = 10$. The three curves correspond to different choices of gluino masses as indicated on the figure.

4) $BR(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\gamma)$ as a function of $\tan\beta$ for two different sets of gluino masses and choices of $\mu$. 

