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Report of the Supersymmetry Subgroup to the  
Workshop on Experiments, Detectors, and  
Experimental Areas for the Supercollider,  
Berkeley, CA, July 7-17, 1987

### Techniques for Finding Supersymmetry at the SSC

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## Techniques for Finding Supersymmetry at the SSC\*

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### Abstract

We examine the signatures at the SSC for supersymmetry for much of the (minimal) supersymmetric model parameter space. In particular, we survey the decay modes and signatures of gluinos and squarks. Gluinos (squarks) decay to two (one) jets and a chargino or neutralino ( $\tilde{\chi}$ ). This  $\tilde{\chi}$  may be the (stable) lightest supersymmetric particle, LSP (and lead to missing energy). Or  $\tilde{\chi}$  may have a two-body decay to another  $\tilde{\chi}$  plus a  $W$ ,  $Z$  or Higgs boson. Finally, it may have a three-body decay to the LSP plus  $q\bar{q}$ ,  $e\nu$ ,  $\mu\nu$ ,  $ee$  or  $\mu\mu$ . Only for very light gluinos and squarks is the decay mode containing the LSP dominant. In fact, for gluinos and squarks over 500 GeV, the decays to  $W$  and  $Z$  bosons dominate for much of parameter space. We estimate the backgrounds for the case in which both gluinos decay to  $Z$  bosons. The decays of gluinos and squarks which go directly to the LSP lead to very large missing energy. We report the initial results of a study of the backgrounds for this process.

*Report of the Supersymmetry Subgroup of the Workshop on Experiments, Detectors, and Experimental Areas for the Supercollider, July 7-17, 1987, Berkeley, CA.*

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## 1. Introduction

Attention has been focused on supersymmetry by subgroups at several Supercollider workshops during the last few years. New theoretical and experimental developments now permit a more sophisticated analysis of techniques for finding supersymmetry than was possible then. The motivation for searching for supersymmetry remains high. The development of superstring theories provided a deeper understanding of the expectations for supersymmetry. For some time theorists have given plausible arguments for why the masses of supersymmetric particles should be 1 TeV or less. Experimentally the lower bounds have now risen to 30-80 GeV depending on the particle.

The primary experimental lessons we can now take advantage of are those learned in analyzing the UA1 data<sup>1,2</sup> for monojets and dijets with missing energy and in searching for the  $t$  quark<sup>3,4</sup>. The UA1 Collaboration made considerable progress in finding techniques for separating signals from backgrounds. One can also make use of the reported mass limits on supersymmetric particles. Theoretically we now understand that it is essential to allow full mixing in the gaugino-higgsino sector, and to avoid making any assumptions concerning the mass of the lightest supersymmetric particle (we do not assume it is almost massless). In this paper our conclusions are not based on a single scenario, but rather on a complete survey of all of parameter space for the minimal supersymmetric model.

At a hadron collider the most copiously produced supersymmetric particles (kinematics allowing) will be the gluino and squarks, which are produced via the strong interactions. For  $\tilde{q}$  and  $\tilde{g}$  masses in the range that have been looked for at the CERN  $S\bar{p}pS$  collider ( $M \lesssim 60$  GeV) the gluino would decay primarily via

$$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0,$$

and the squark (if  $M_{\tilde{q}} < M_{\tilde{g}}$ ) via

$$\tilde{q} \rightarrow q\tilde{\chi}_1^0.$$

$\tilde{\chi}_1^0$  is the lightest neutralino, which we take to be the lightest supersymmetric particle (LSP). Squark or gluino production, in this case, would be signalled<sup>5</sup> by events with jet(s) and missing transverse energy ( $E_T^{miss}$ ), due to the LSP which escapes detection. The UA1 Collaboration,<sup>2</sup> after an analysis of the  $E_T^{miss}$  data sample has recently reported the limits  $M_{\tilde{g}} > 53$  GeV and  $M_{\tilde{q}} > 45$  GeV. These limits are valid for  $m_{\tilde{\chi}_1^0} < 20-30$  GeV. It has also been argued<sup>6</sup> that gluinos and squarks with masses up to 150 - 200 GeV can be searched for at the Fermilab Tevatron. Above this mass range, searches can best be carried out at the next generation of hadron colliders such as the Superconducting Super Collider (SSC). Indeed, it is very possible that no evidence of physics beyond the Standard Model will be seen at the Tevatron, SLC or LEP. Such a result need not be in conflict with supersymmetry as the explanation of the origin of the electroweak scale. Certainly, sensible models of "low-energy supersymmetry"

are easily constructed which have squarks, sleptons and gluinos with masses of the order of 500 GeV and beyond.<sup>7</sup>

In this paper, we are primarily interested in heavy gluinos and squarks which could be discovered at a future supercollider. For each particle we shall study its phenomenology only for the case that it is the lighter of the two particles. The reason for this is simple: if (say) gluinos are heavier than squarks, then they will decay into squarks (via a two-body decay). To study supersymmetry in this case, it would be far more efficient to study squarks which are produced directly. The detection of gluinos would then be a “second generation” type of experiment. Thus, for the rest of this paper, we assume when we study gluinos that  $M_{\tilde{g}} < M_{\tilde{q}}$  and assume  $M_{\tilde{q}} < M_{\tilde{g}}$  when we study squarks. With these two assumptions, the two-body decays  $\tilde{g} \rightarrow \tilde{q}q$  and  $\tilde{q} \rightarrow \tilde{g}q$  are forbidden. For gluinos one must consider all kinematically allowed decays of the type

$$\begin{aligned}\tilde{g} &\rightarrow q\bar{q}'\tilde{\chi}_i^\pm \\ \tilde{g} &\rightarrow q\bar{q}\tilde{\chi}_i^0.\end{aligned}\tag{1}$$

and for squarks one must consider all kinematically allowed decays of the type

$$\begin{aligned}\tilde{q} &\rightarrow q'\tilde{\chi}_i^\pm \\ \tilde{q} &\rightarrow q\tilde{\chi}_i^0.\end{aligned}\tag{2}$$

where the index  $i$  runs over all charginos or neutralinos.

We focus on the predictions for the above decays in the minimal supersymmetric extension of the Standard Model, specified in detail in refs. 8 and 9. In this model the spin-1/2 superpartners of the two Higgs doublets combine with the superpartners of the  $W^\pm$  and of the  $\gamma, Z$  to yield two chargino mass eigenstates,  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^\pm$ , and four neutralino mass eigenstates,  $\tilde{\chi}_1^0$ ,  $\tilde{\chi}_2^0$ ,  $\tilde{\chi}_3^0$ , and  $\tilde{\chi}_4^0$ ; the labelling is according to increasing mass. The importance of allowing neutralinos and charginos in the final state with arbitrary mixing angles must be stressed. One often finds analyses presented where special assumptions have been made (*e.g.* that the lightest neutralino is a pure photino). Apart from the fact that such assumptions are arbitrary, one can sometimes be led to wrong conclusions.

In general there are many allowed decay channels for gluinos and squarks. In particular, it is important to note that several of the charginos and neutralinos are usually substantially lighter than the gluino and squark. Thus the probability that a heavy gluino or squark will decay directly into jets and the LSP may be rather small; decays to a heavier chargino or neutralino, which eventually cascades down into the LSP could be (and, in fact, are) dominant.<sup>10</sup> Of special interest are decays to charginos and neutralinos that are heavy enough that they will, in turn, decay into a lighter chargino or neutralino plus a  $W$  or  $Z$ <sup>11,12,13</sup>. The resulting signature for gluino production is striking. In this paper, we will assess the relative importance of such decays as a function of the gluino (or squark) mass and other parameters of the supersymmetric theory.

Let us now discuss the parameters of the minimal supersymmetric model. The mass matrices for the  $\tilde{\chi}^\pm$  and  $\tilde{\chi}^0$  sectors depend on three unknown mass scales— $\mu$ ,  $M_2$ , and  $M_1$ —in addition to the Higgs vacuum expectation values to be discussed shortly. Here  $\mu$  is a supersymmetric Higgs mass parameter and  $M_2$  and  $M_1$  are gaugino mass parameters associated with the soft breaking of supersymmetry in the  $SU(2)$  and  $U(1)$  sectors. We will follow the common practice of reducing the parameter freedom by assuming that these latter two mass parameters are related to the gaugino mass of the  $SU(3)$  subgroup,  $M_3$  (which is equal to the gluino mass,  $M_{\tilde{g}}$ ), by requiring that the three mass scales are equal at some grand unification scale. Using the notation of refs. 8 and 9, where  $M_2 \equiv M$  and  $M_1 \equiv (3/5)M'$ , this implies

$$\begin{aligned} M &= \frac{g^2}{g_s^2} M_{\tilde{g}} \\ M' &= \frac{5g'^2}{3g_s^2} M_{\tilde{g}}. \end{aligned} \tag{3}$$

Turning to the Higgs sector of the minimal model, we emphasize that it contains exactly two doublets,  $H_1$  and  $H_2$ . The vacuum expectation values of the neutral members of these two doublets,  $v_1$  and  $v_2$ , give masses to the down and up-type quarks respectively. Of the eight degrees of freedom, three are absorbed in giving mass to the  $W^\pm$  and  $Z$ , leaving two neutral scalar Higgs bosons,  $H_1^0$  and  $H_2^0$ , a neutral pseudoscalar Higgs boson,  $H_3^0$ , and a pair of charged Higgs bosons,  $H^\pm$ . In the minimal model there are strong constraints upon the tree-level masses of these various Higgs bosons. Using the notation

$$\tan \beta = v_2/v_1, \tag{4}$$

one finds that by fixing  $\tan \beta$  and one of the Higgs masses (say,  $m_{H^\pm}$ ), all the other tree-level Higgs masses are determined:<sup>14</sup>

$$m_{H_3^0}^2 = m_{H^\pm}^2 - m_W^2 \tag{5}$$

$$m_{H_1^0, H_2^0}^2 = \frac{1}{2} \left( m_{H_3^0}^2 + m_Z^2 \pm \sqrt{(m_{H_3^0}^2 + m_Z^2)^2 - 4m_Z^2 m_{H_3^0}^2 \cos^2 2\beta} \right). \tag{6}$$

Note that  $H_2^0$  is always lighter than the  $Z$  and is particularly light if  $\tan \beta$  is near 1 or if  $m_{H^\pm}$  is near  $m_W$ . Hence, one would expect  $H_2^0$  to play a central role in the phenomenology of chargino and neutralino decays. Depending upon the choice of  $m_{H^\pm}$  some, or all, of the remaining Higgs bosons may also be light enough to be important in neutralino and chargino decays (note though that  $H^\pm$  is always heavier than the  $W$  boson). These considerations become important for the discussion of gluinos which do not decay directly into the LSP.

Our analysis always accounts for the existence of a region of  $\mu$  for which the mass of the lightest chargino is less than the experimental lower bound which we take to be  $\sim 30 \text{ GeV}$

(the boundaries of this  $\mu$  region depend on  $M_{\tilde{g}}$ ). We use the above bound as a conservative limit based on the PETRA bound of  $23 \text{ GeV}^{15}$  and the limit of ref. 16, inferred from UA1 data, of  $\sim 40 \text{ GeV}$ . In what follows we shall only present results for  $\mu$  values that do not violate this bound.

## 2. Gluino Decays

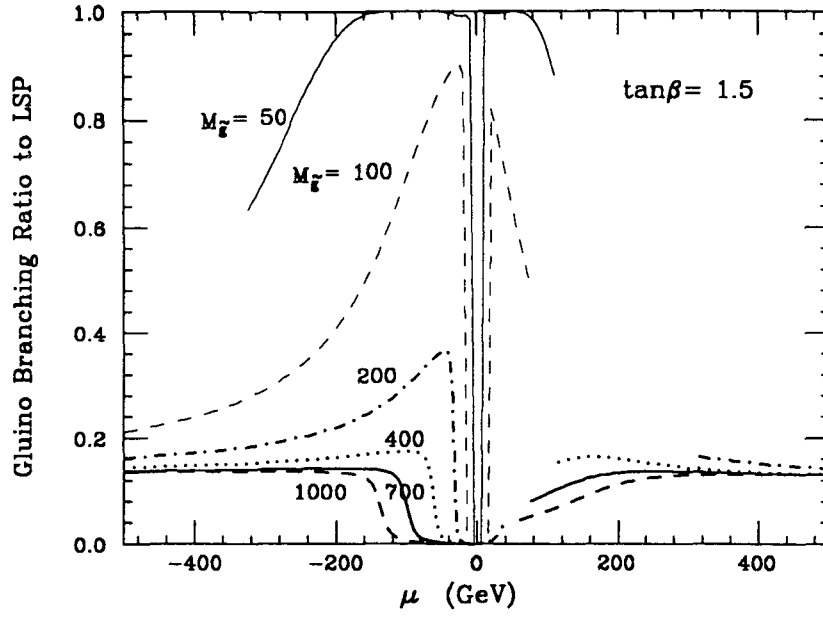
As stated in the Introduction, when studying gluinos, we assume that  $M_{\tilde{g}} < M_{\tilde{q}}$ . For simplicity, we shall take six generations of  $\tilde{q}_L$  and  $\tilde{q}_R$  to be degenerate in mass. The formulae for gluino decay widths we use in obtaining branching ratios are given in Ref. 12. The only approximation that we make is to take the quarks which appear in the final state to be massless. The overall effect of finite quark mass on gluino branching ratios is small. Without loss of generality we may restrict  $\beta$  to lie between 0 and  $\pi/2$ . We make the assumption of  $CP$  invariance in the neutralino and chargino sectors, so  $M, M'$  and  $\mu$  can be taken as real. The parameter  $M$  is taken as positive whereas  $\mu$  can have either sign. We assume that the lightest supersymmetric particle (LSP) is the lightest neutralino,  $\tilde{\chi}_1^0$ ; it is assumed to be stable and will escape collider detectors as missing energy. Finally, for our numerical work we have taken  $M_{\tilde{q}} = 1.5M_{\tilde{g}}$ , but our results are insensitive to this choice.

In presenting our results for gluino decays to neutralinos and charginos, we generally consider two representative values for  $\tan \beta$ : 1.5 and 4. Results for  $\tan \beta = 1$  are always very similar to those at  $\tan \beta = 1.5$ . Further, all results are unchanged if  $\tan \beta \rightarrow \cot \beta$ . Finally, recall that we shall only plot results corresponding to  $\mu$  values that yield  $m_{\tilde{\chi}_1^+} > 30 \text{ GeV}$ .

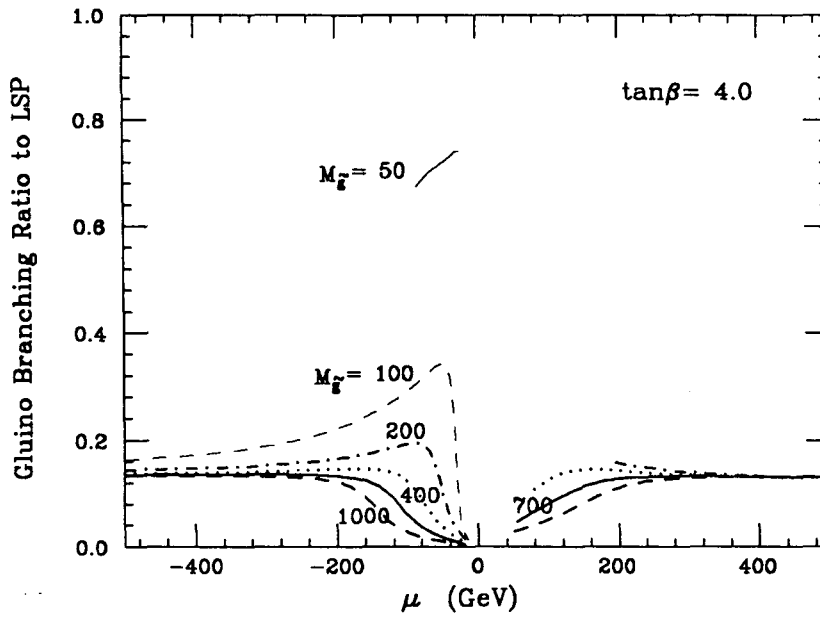
We begin by considering the branching ratio for gluino decay to the LSP,  $\tilde{\chi}_1^0$ . The gluino searches at the CERN  $SppS$  have relied on this branching ratio being large for light gluinos. In figs. 1 and 2 the branching ratio for  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$  is plotted as a function of  $\mu$  for a series of  $M_{\tilde{g}}$  values ranging from  $M_{\tilde{g}} = 50 \text{ GeV}$  to  $M_{\tilde{g}} = 1 \text{ TeV}$ , taking  $\tan \beta = 1.5$  and  $\tan \beta = 4$ . We see that for  $M_{\tilde{g}} = 50 \text{ GeV}$  there is a range of  $\mu$  over which the branching ratio for this decay is unity (when  $\tan \beta$  is not too large). However, even for this low  $M_{\tilde{g}}$  value, the branching ratio for this decay decreases rapidly for  $|\mu| \gtrsim 250 \text{ GeV}$ . The branching ratio to the LSP also vanishes for  $|\mu|$  very near 0. This is easily understood, since in this region the LSP is dominantly higgsino.

As we move to higher  $M_{\tilde{g}}$  values, figs. 1 and 2 make it clear that the branching ratio to  $\tilde{\chi}_1^0$  decreases very rapidly, especially in the case of  $\tan \beta = 4$ . Indeed, once  $M_{\tilde{g}} \gtrsim 400 \text{ GeV}$  this branching ratio is essentially zero in the vicinity of  $\mu = 0$  and rises to around 0.14 at large  $|\mu|$ .





**Figure 1:** The branching ratio for  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$  as a function of  $\mu$  for a series of  $M_{\tilde{g}}$  values (in GeV units), where  $\tilde{\chi}_1^0$  is the lightest supersymmetric particle (LSP). For this figure we take  $\tan\beta = 1.5$ . Sections of the curves that are not plotted, both here and in all succeeding graphs, correspond to parameter choices which yield  $M_{\tilde{\chi}_1^+} < 30 \text{ GeV}$ .

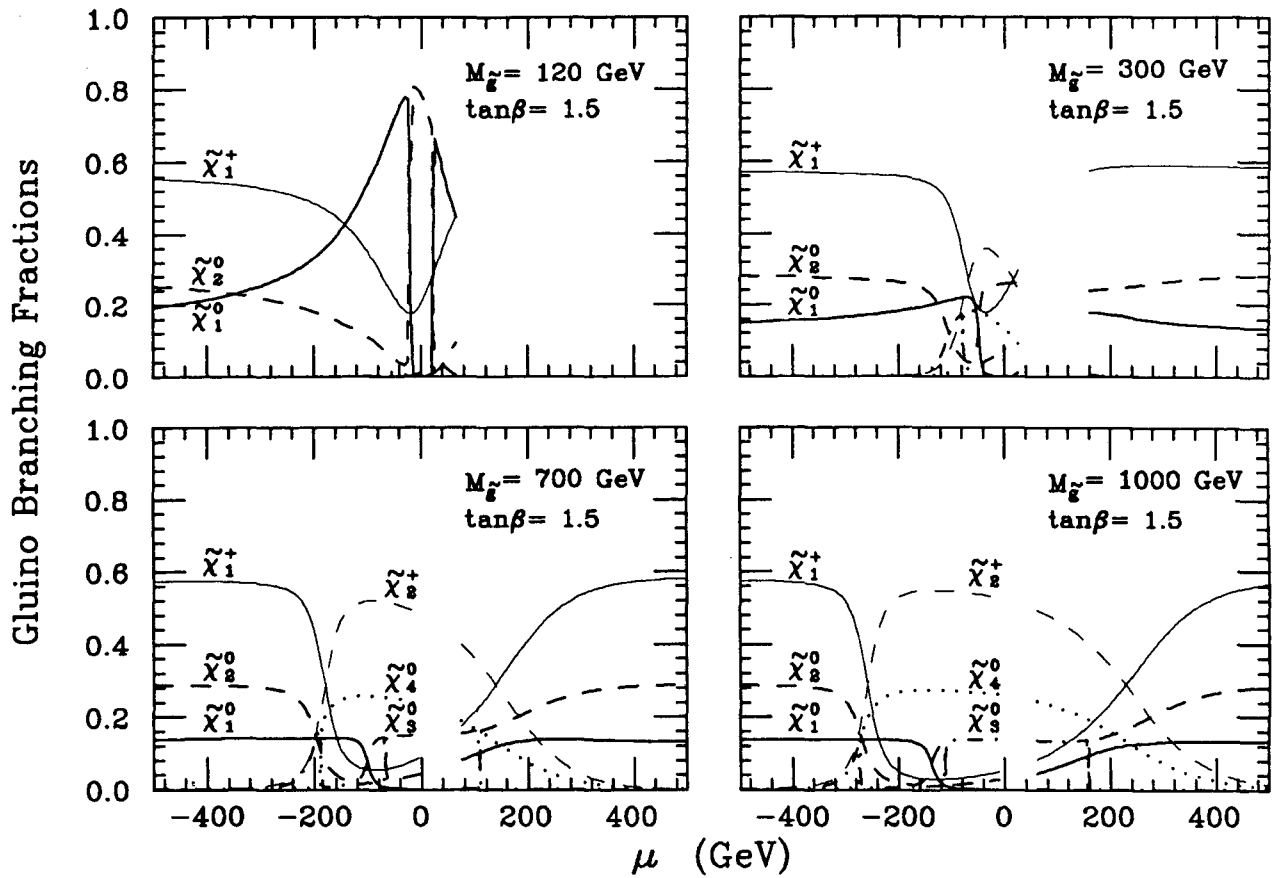


**Figure 2:** We present the same plots as in fig. 1, but for  $\tan\beta = 4$ .

These results have dramatic consequences for gluino searches. We would like to caution the reader that in many (all?) previous studies of gluino detection at future colliders, it has been assumed that  $BR(\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}) = 100\%$ . It is evident from figs. 1-2 that this is an incorrect assumption. In fact, for heavy gluinos (roughly  $M_{\tilde{g}} \gtrsim 600 \text{ GeV}$ ), we find a strict inequality  $BR(\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0) \leq 0.14$ , independent of the values of  $\tan\beta$ ,  $\mu$  and  $M_{\tilde{g}}$  (assuming, of course, that  $M_{\tilde{g}} > M_{\tilde{q}}$ ). This means that *in  $\tilde{g}\tilde{g}$  production, the probability of having direct decay of both gluinos into the LSP is less than 2%*. However, it is not necessary to have both gluinos decay directly to the LSP in order to obtain large  $E_T^{miss}$ . The  $E_T^{miss}$  spectrum from events where one gluino has decayed directly to the LSP but the other gluino has any other decay mode, is not radically different from the two-gluinos-to-LSP case, and it is far more productive to look for the former case.

Since the branching ratio for gluino decay to the LSP is not large at high  $M_{\tilde{g}}$  values, it is clear that modes involving the heavier charginos and neutralinos are becoming important. In order to display in more detail the various modes, we present in figs. 3 and 4 plots of gluino branching ratios showing all the  $q\bar{q}'\tilde{\chi}^\pm$  and  $q\bar{q}\tilde{\chi}^0$  channels. In each figure the branching ratios for  $\tilde{\chi}_i^0$  ( $i = 1, 2, 3, 4$ ) and  $\tilde{\chi}_j^\pm$  ( $j = 1, 2$ ) are presented as a function of  $\mu$  for  $M_{\tilde{g}} = 120, 300, 700$  and  $1000 \text{ GeV}$ . The two different figures correspond to our two representative  $\tan\beta$  choices:  $\tan\beta = 1.5$  and  $4$ . Most apparent is the presence of three very distinct branching ratio levels. At large  $|\mu|$  these correspond to  $\tilde{g}$  decay to  $\tilde{\chi}_1^\pm$ ,  $\tilde{\chi}_2^0$  and  $\tilde{\chi}_1^0$  in order of decreasing magnitude. At small  $|\mu|$  these same plateau values emerge, but correspond to  $\tilde{g}$  decay to  $\tilde{\chi}_2^\pm$ ,  $\tilde{\chi}_4^0$  and  $\tilde{\chi}_3^0$ , again in order of decreasing magnitude. That the dominant modes should switch from the heaviest states at small  $|\mu|$  to the lightest states at large  $|\mu|$  is easily explained by the fact that the virtual  $\tilde{q}$  in  $\tilde{g}$  decay couples primarily to the gaugino components of the  $\tilde{\chi}$ 's. At large  $|\mu|$  the heavier states are dominated by the Higgsino components (recall that  $\mu$  is a Higgsino mass parameter), and their couplings to the virtual  $\tilde{q}$  are suppressed in amplitude by a factor of order  $m_q/m_W$ . On the other hand, at small  $|\mu|$  the heavier states are dominated by the gaugino components whose couplings to the virtual  $\tilde{q}$  are of standard electroweak strength. An examination of the neutralino and chargino mass matrices makes it clear that this switchover occurs when  $|\mu| \sim M$ , which, given the grand unification relations of eq. (3), means  $|\mu| \sim M_{\tilde{g}}/4$ . The importance of this crossover point will be apparent in much of the analysis and in the figures which follow.

Simple analytic expressions for the three plateau levels are derived in Ref. 12. From these one finds that for heavy gluinos, independent of the values of  $M_{\tilde{g}}$ ,  $M_{\tilde{q}}$  and all other parameters of the supersymmetric model, the values of the three plateaus of figs. 3 and 4 are about 0.58, 0.28 and 0.14. This, in particular, implies that for heavy gluinos,  $BR(\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0) \leq 0.14$ , as remarked earlier.



**Figure 3:** We give the branching ratios for  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_i^0$  and  $\tilde{g} \rightarrow q\bar{q}'\tilde{\chi}_j^\pm$  ( $i = 1, 2, 3, 4$  and  $j = 1, 2$ ) as a function of  $\mu$  for four  $M_{\tilde{g}}$  values and  $\tan\beta = 1.5$ . The various curves correspond to: light solid line =  $\tilde{\chi}_1^\pm$ ; light dashed line =  $\tilde{\chi}_2^\pm$ ; heavy solid line =  $\tilde{\chi}_1^0$ ; heavy dashed line =  $\tilde{\chi}_2^0$ ; heavy dash-dot line =  $\tilde{\chi}_3^0$ ; and heavy dotted line =  $\tilde{\chi}_4^0$ .

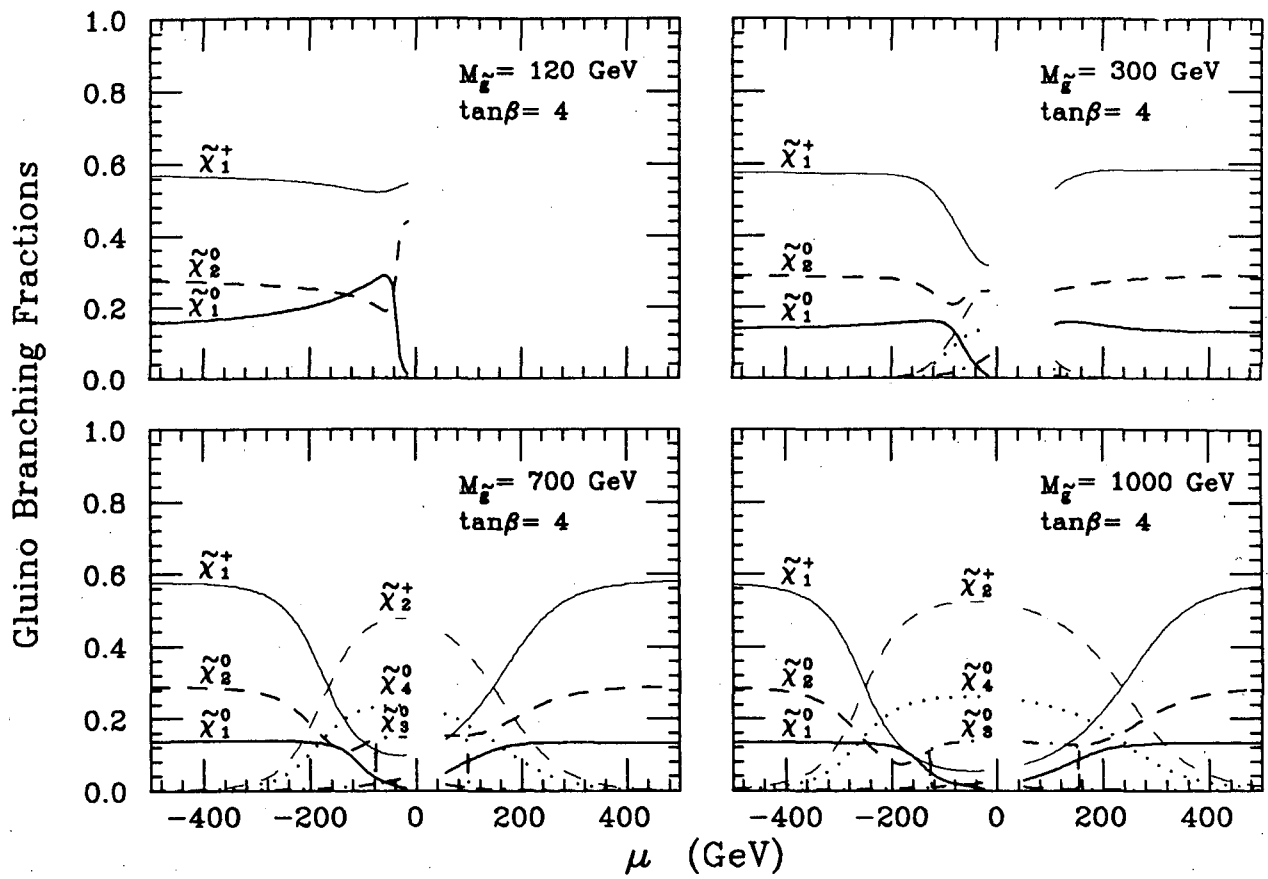


Figure 4: The same as for fig. 3, but with  $\tan\beta = 4.0$ .

Next we discuss the decay modes of the  $\tilde{\chi}^0$  and  $\tilde{\chi}^\pm$  which are produced in the decay of the gluino. Full results and formulae for these decays appear in a paper by Gunion and Haber.<sup>17</sup> The following two-body decays are allowed:

$$\begin{aligned}
\tilde{\chi}_i^0 &\rightarrow \tilde{\chi}_j^0 + Z^0 \\
\tilde{\chi}_i^0 &\rightarrow \tilde{\chi}_j^\pm + W^\mp \\
\tilde{\chi}_i^\pm &\rightarrow \tilde{\chi}_j^0 + W^\pm \\
\tilde{\chi}_i^\pm &\rightarrow \tilde{\chi}_j^\pm + Z^0.
\end{aligned}
\tag{7}$$

$$\begin{aligned}
\tilde{\chi}_i^0 &\rightarrow \tilde{\chi}_j^0 + H_k^0 \\
\tilde{\chi}_i^0 &\rightarrow \tilde{\chi}_j^\pm + H^\mp \\
\tilde{\chi}_i^\pm &\rightarrow \tilde{\chi}_j^0 + H^\pm \\
\tilde{\chi}_i^\pm &\rightarrow \tilde{\chi}_j^\pm + H_k^0
\end{aligned}
\tag{8}$$

(where  $k = 1, 2,$  or  $3$ ).

If any of these two-body processes is allowed, they will certainly dominate any three-body decays mediated by virtual squark (or slepton) exchange. It is important to realize that two-body decays into a Higgs boson (especially the lightest Higgs) will, in general, be competitive with the production of vector bosons. By specifying  $m_{H^\pm}$  in addition to those parameters already delineated for the neutralino/chargino sector, the widths for the decays to Higgs bosons may be computed. The constraints on the Higgs masses described above imply that  $H_2^0$  is very light if either  $\tan\beta$  is near 1 or  $m_{H^\pm}$  is near  $m_W$ . In such cases, the decays  $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 + H_2^0$  and  $\tilde{\chi}_i^+ \rightarrow \tilde{\chi}_j^+ + H_2^0$  are certain to be important modes over nearly all of the supersymmetric parameter space. (If  $m_{H^\pm}$  is near  $m_W$ , then  $H_3^0$  is also light and can be similarly produced.)

In order to gain a more complete understanding of the phase space, both for  $\tilde{g}$  decays to the  $\tilde{\chi}^\pm$ 's and  $\tilde{\chi}^0$ 's and for  $\tilde{\chi}^\pm$  and  $\tilde{\chi}^0$  decays in the modes (7) and (8), we present in fig. 5 results for the masses of the various charginos and neutralinos for the four  $M_{\tilde{g}}$  values considered in figs. 3 and 4, taking  $\tan\beta = 1.5$ . (The mass spectra for  $\tan\beta = 4$  are almost indistinguishable.) There are a number of features of these results that will be useful in the following discussions.

1. For all choices of  $M_{\tilde{g}}$  there are regions near  $\mu = 0$  where the  $\tilde{\chi}_1^0$  and  $\tilde{\chi}_1^\pm$  are very light. Generally, the  $\tilde{\chi}_1^0$  is the LSP but there is always a narrow region of small positive  $\mu$  for which  $\tilde{\chi}_1^\pm$  is the LSP. However, the bounds discussed earlier<sup>15, 16</sup> imply that  $m_{\tilde{\chi}_1^\pm}$  must be  $\gtrsim 30$  GeV. From fig. 5 we see that this always rules out a set of small positive  $\mu$  values, including those for which  $m_{\tilde{\chi}_1^\pm} < m_{\tilde{\chi}_1^0}$ . For these  $\mu$  values we do not plot branching ratios in our various graphs.

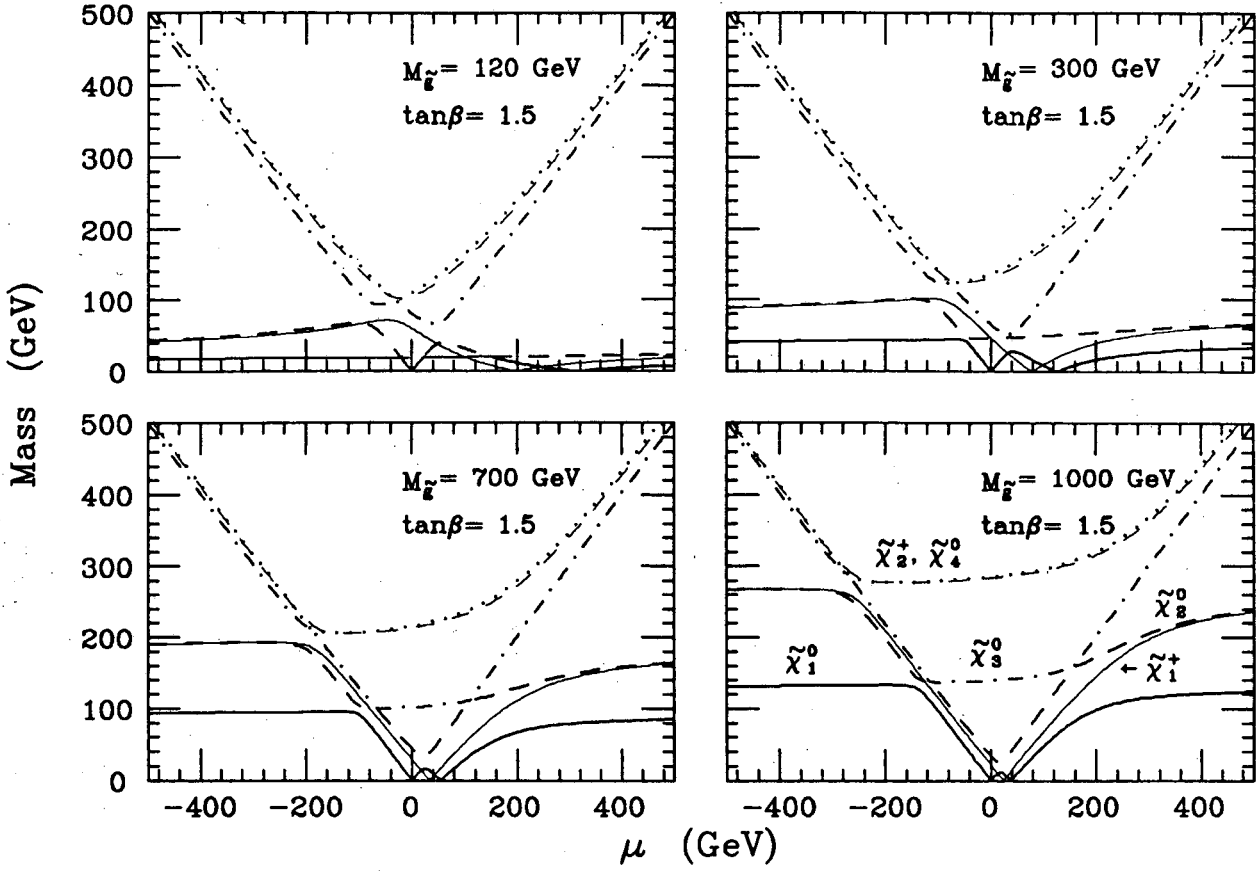


Figure 5: We present, using notation completely parallel to that of figs. 3 and 4, the masses of the  $\tilde{\chi}^0$ 's and  $\tilde{\chi}^{\pm}$ 's, for the same four gluino mass values at  $\tan\beta = 1.5$ .

2. When  $M_{\tilde{g}} \gtrsim 700 \text{ GeV}$ , fig. 5 shows that at large  $|\mu|$  not only are  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  heavier than the  $Z$ , but so is the LSP ( $\tilde{\chi}_1^0$ ), contrary to old “theorems”.<sup>18</sup>
3. Even for relatively low  $M_{\tilde{g}}$  values, the  $\tilde{\chi}_2^\pm$ ,  $\tilde{\chi}_4^0$  and  $\tilde{\chi}_3^0$  can have masses that are larger than the  $\tilde{\chi}_1^\pm$ ,  $\tilde{\chi}_2^0$  and  $\tilde{\chi}_1^0$  masses by at least  $m_Z$ , so that the potential for the two-body decays listed in eq. (7) exists for decays with an initial  $\tilde{\chi}_4^0, \tilde{\chi}_3^0, \tilde{\chi}_2^\pm$  and a final  $\tilde{\chi}_2^0, \tilde{\chi}_1^0, \tilde{\chi}_1^\pm$ .
4. The  $\tilde{\chi}_4^0$  and  $\tilde{\chi}_2^\pm$  are approximately degenerate, implying that chain decay of either particle into the other plus a  $W$  or  $Z$  is forbidden. A similar statement also applies to the  $\tilde{\chi}_3^0$  in the region  $|\mu| \gtrsim M_{\tilde{g}}/4$ , where its mass is only slightly less than those of  $\tilde{\chi}_4^0$  and  $\tilde{\chi}_2^\pm$ . However, for  $|\mu| \lesssim M_{\tilde{g}}/4$  and large  $M_{\tilde{g}}$  the  $\tilde{\chi}_3^0$  mass can be significantly below the masses of  $\tilde{\chi}_4^0$  and  $\tilde{\chi}_2^\pm$ , and the decays  $\tilde{\chi}_4^0 \rightarrow Z\tilde{\chi}_3^0$  and  $\tilde{\chi}_2^\pm \rightarrow W^\pm\tilde{\chi}_3^0$  are phase space allowed.
5. Finally, for large gluino mass,  $M_{\tilde{g}} \gtrsim 800 \text{ GeV}$ , the decays  $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^\pm$  and  $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z$  become possible at large  $|\mu| \gtrsim M_{\tilde{g}}/4$ .

We now survey the basic gluino decay chains that lead to a signature of great interest:<sup>19</sup>

$$\tilde{g} \rightarrow jet(s) + W(\text{or } Z) + E_T^{\text{miss}}. \quad (9)$$

We present our results by plotting

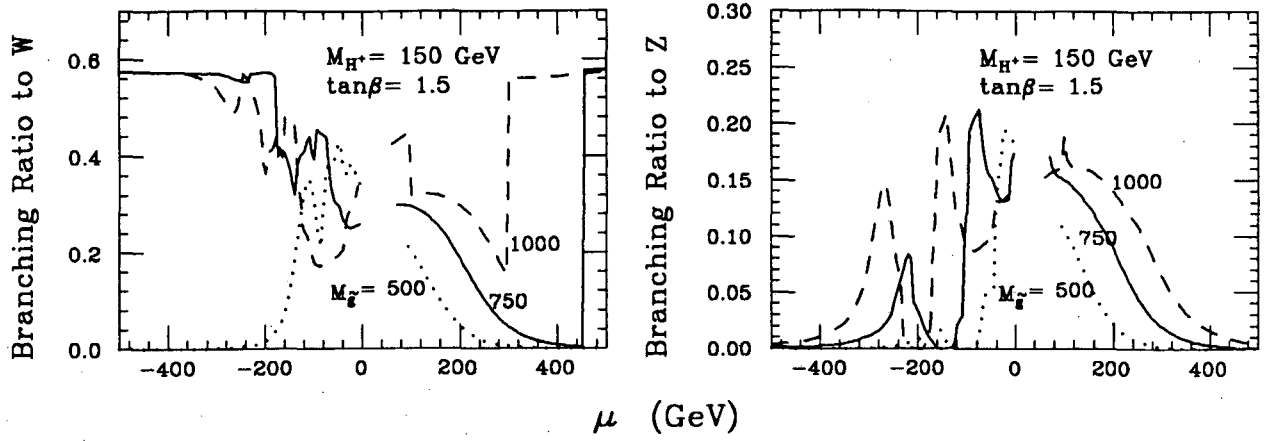
$$BR[\tilde{g} \rightarrow \tilde{\chi}_{1,2}^\pm(\rightarrow W^\pm)] + BR[\tilde{g} \rightarrow \tilde{\chi}_{2,3,4}^0(\rightarrow W^\pm)] \quad (10)$$

and

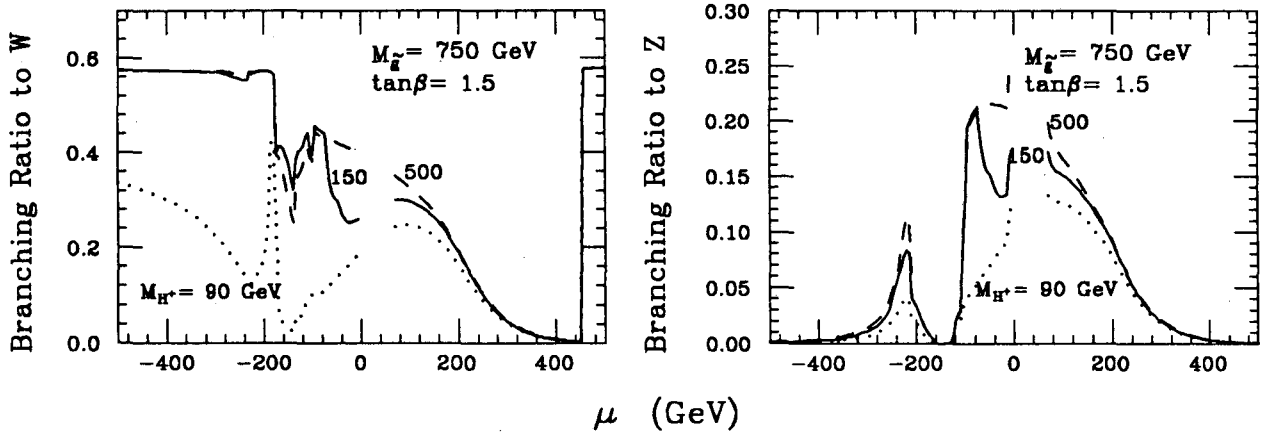
$$BR[\tilde{g} \rightarrow \tilde{\chi}_{1,2}^\pm(\rightarrow Z)] + BR[\tilde{g} \rightarrow \tilde{\chi}_{2,3,4}^0(\rightarrow Z)] \quad (11)$$

in figs. 6 and 7. We plot these branching ratios as a function of  $\mu$  for various values of  $M_{\tilde{g}}$  and  $m_{H^\pm}$  (there is little dependence on  $\tan\beta$ ). The many sudden jumps in the curves occur due to two physical effects: (1) sudden changes in identity of a given neutralino or chargino, as mass eigenstates undergo level crossing and switch from being dominantly higgsino to dominantly gaugino; (2) the sudden onset or disappearance of the various 2-body decay modes, as determined by phase space.

The results are easily summarized. When  $|\mu| \lesssim M_{\tilde{g}}/4$ , and the heavier chargino and neutralino states dominate the  $\tilde{g}$  decays, the branching ratios to  $W$ 's and  $Z$ 's become very significant. This is true so long as  $M_{\tilde{g}} \gtrsim 300 \text{ GeV}$ . A light  $\tilde{\chi}_1^\pm$ ,  $\tilde{\chi}_2^0$  or  $\tilde{\chi}_1^0$  is produced along with the  $W$  or  $Z$ —a  $\tilde{\chi}_3^0$  is essentially never produced by  $\tilde{\chi}_2^\pm$  and  $\tilde{\chi}_4^0$  decays. (Even though the decays  $\tilde{\chi}_2^\pm \rightarrow W^\pm\tilde{\chi}_3^0$  and  $\tilde{\chi}_4^0 \rightarrow Z\tilde{\chi}_3^0$  are phase space allowed at large  $M_{\tilde{g}}$  and  $|\mu| \lesssim M_{\tilde{g}}/4$ , these decays are strongly suppressed by neutralino mixing angle factors.)



**Figure 6:** The gluino branching ratios to  $W$  and  $Z$  (see eqs. (10) and (11)) as a function of  $\mu$  for  $M_{\tilde{g}} = 500$  (dotted), 750 (solid), and 1000  $GeV$  (dashed) at  $\tan\beta = 1.5$ . We have taken  $m_{H^\pm} = 150 GeV$ . As in previous figures, omitted portions of the curves correspond to parameter regions where  $M_{\tilde{\chi}_1^+} < 30 GeV$ .



**Figure 7:** The gluino branching ratios to  $W$  and  $Z$  (see eqs. (10) and (11)) as a function of  $\mu$  for  $M_{\tilde{g}} = 750 GeV$  and  $\tan\beta = 1.5$  for 3 values of  $m_{H^\pm}$ : 90 (solid), 150 (dashed), and 500  $GeV$  (dotted). As in previous figures, omitted portions of the curves correspond to parameter regions where  $M_{\tilde{\chi}_1^+} < 30 GeV$ .



For  $|\mu| \gtrsim M_{\tilde{g}}/4$  we have seen that the lighter neutralinos and charginos dominate the  $\tilde{g}$  decays, and it is only for very large  $M_{\tilde{g}}$  ( $\gtrsim 600 \text{ GeV}$ ) that  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  become heavy enough that they can decay to  $W^\pm \tilde{\chi}_1^0$  and  $Z \tilde{\chi}_1^0$ , respectively. However, the  $\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0$  decay is severely suppressed relative to the  $\tilde{\chi}_2^0 \rightarrow H_2^0 \tilde{\chi}_1^0$  mode. Thus, for large  $M_{\tilde{g}}$  and  $|\mu| \gtrsim M_{\tilde{g}}/4$  we obtain the result, apparent in the figures, that gluino decay *will* typically contain a  $W$  but *not* a  $Z$ .

Of course, gluinos will not always decay either to  $W$ 's,  $Z$ 's, and Higgs (using the two-body  $\tilde{\chi}$  decays) or *directly* to the LSP. Some of the time they will decay to two SM fermions plus a  $\tilde{\chi}$  which decays in a three-body mode, yielding five particles in the  $\tilde{g}$  final state (prior to further decays). We term such decays ‘five-body’ modes.

We now summarize the possible signatures for gluino decay. In the discussion below, we sometimes refer to the quark and lepton modes. These result from the secondary (and tertiary) decays of the chargino or neutralino produced in the gluino decay chain. Their relative branching ratios are determined by the gaugino content of the particular  $\tilde{\chi}$  state involved (since we neglect all final state quark and lepton masses). When we refer to leptonic modes, we are summing only over electrons and muons. We have not considered final states involving tau leptons since these lead to more complicated signatures.

Many of our results on gluinos signatures are summarized in fig. 8. The “five-body” gluino decays include:

$$\begin{aligned} & q\bar{q} q\bar{q} \tilde{\chi}_1^0 \\ & q\bar{q} e^+ e^- \tilde{\chi}_1^0 \\ & q\bar{q} \mu^+ \mu^- \tilde{\chi}_1^0 \\ & q\bar{q}' e^+ \nu \tilde{\chi}_1^0 \\ & q\bar{q}' \mu^- \bar{\nu} \tilde{\chi}_1^0. \end{aligned}$$

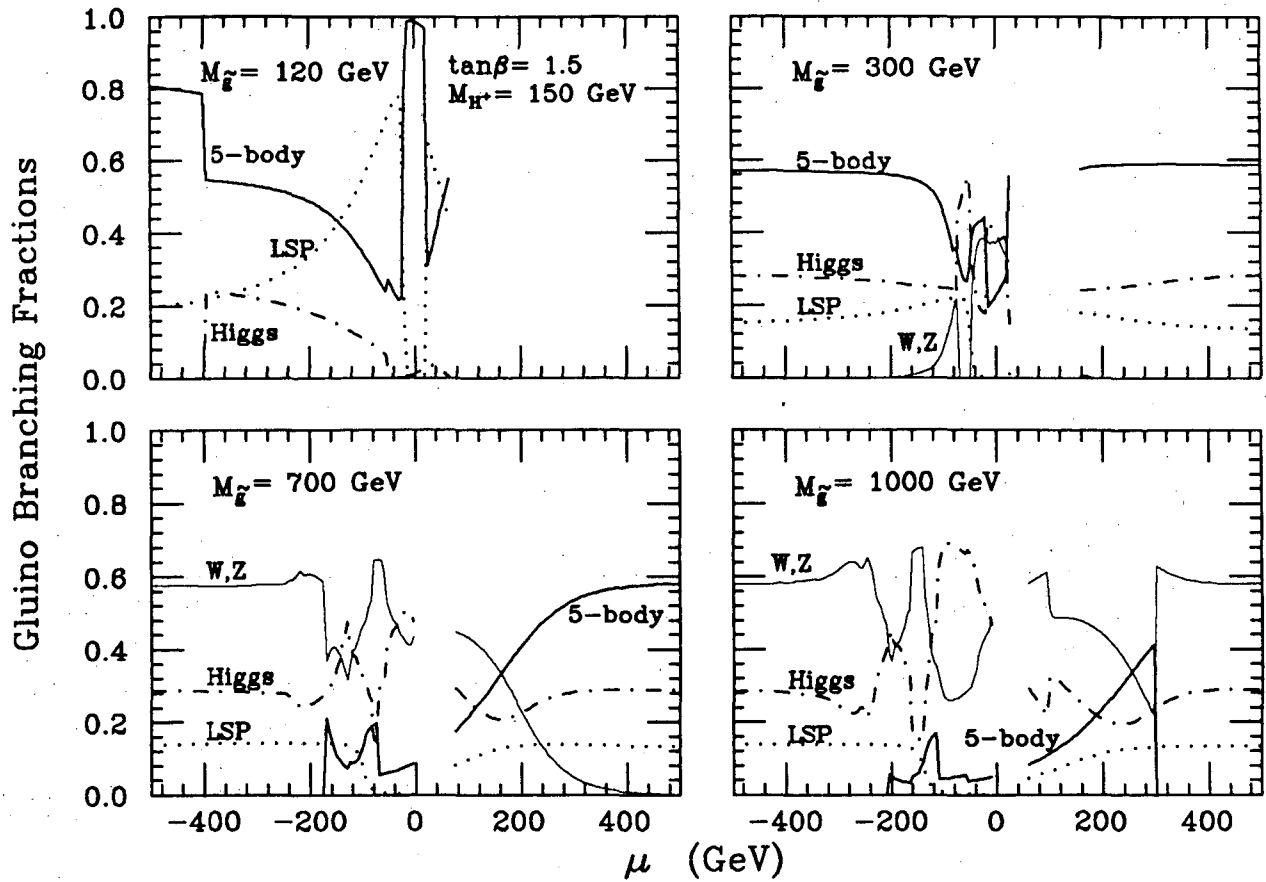
The curves in fig. 8 labelled “LSP” refer to decays directly to the  $\tilde{\chi}_1^0$  (the LSP):

$$q\bar{q} \tilde{\chi}_1^0.$$

Decays to  $W$  and  $Z$  bosons include:

$$\begin{aligned} & q\bar{q}' W(\text{or } Z) \tilde{\chi}_1^0. \\ & q\bar{q} q\bar{q} Z \tilde{\chi}_1^0 \\ & q\bar{q} e^+ e^- Z \tilde{\chi}_1^0 \\ & q\bar{q}' \mu^+ \nu Z \tilde{\chi}_1^0. \end{aligned}$$

The first mode occurs when the initial gluino decay product was  $\tilde{\chi}_1^\pm$  or  $\tilde{\chi}_2^0$ . The others occur when the initial product is  $\tilde{\chi}_2^\pm$  or  $\tilde{\chi}_4^0$ , and these cascade via another  $\tilde{\chi}^0$  or  $\tilde{\chi}^\pm$ .



**Figure 8:** The branching ratios for gluino decay into the four different categories of tree-level accessible final states: 1) 5-body modes with no real  $W$ 's,  $Z$ 's, or Higgs; 2) the LSP ( $\tilde{\chi}_1^0$ ) directly produced in association with  $q\bar{q}$ ; 3) any state with a real  $W$  or real  $Z$ ; and 4) any state with a Higgs of any type. The branching ratios are presented for four different  $M_{\tilde{g}}$  values as a function of  $\mu$ , taking  $\tan\beta = 1.5$  and  $m_{H^\pm} = 150$  GeV. Modifications arising from varying these parameters are described in the text.

Among the gluino decays containing a Higgs boson are:

$$q\bar{q} H^0(\text{or } H^+) \tilde{\chi}_1^0$$

$$q\bar{q} q\bar{q} H^0(\text{or } H^+) \tilde{\chi}_1^0$$

$$q\bar{q} e^+ e^- H^0(\text{or } H^+) \tilde{\chi}_1^0.$$

Again the first mode occurs when the initial gluino decay product was  $\tilde{\chi}_1^\pm$  or  $\tilde{\chi}_2^0$ . The others occur when the initial product is  $\tilde{\chi}_2^\pm$  or  $\tilde{\chi}_4^0$ , and these cascade via another  $\tilde{\chi}^0$  or  $\tilde{\chi}^\pm$ .

Next, we must remember that gluinos are actually pair produced at a hadron collider and that the above final state structure applies to the decay of each gluino. An incredible variety of search modes emerges. While many spectacular signatures with reasonable event rates are possible, the typical gluino-gluino event is extremely complex and probably cannot be distinguished from background. The exact scenario, of course, depends upon both  $M_{\tilde{g}}$  and  $\mu$ . We list below some promising modes as a function of  $M_{\tilde{g}}$  and  $\mu$ , along with their event rates at the SSC. Our purpose in this section is *not* to study these modes (or their backgrounds), but to identify some signatures deserving of further examination. The event rates shown do *not* take into account either efficiencies or cuts. Large numbers of events do not necessarily mean the signal is observable. It is fairly straightforward to transcribe the discussion below to any other supercollider, once the total  $\tilde{g}\tilde{g}$  cross-sections have been computed. The following results are found in detail in Ref. 12

The total cross-sections at the SSC for gluinos of masses 120, 300, 700 and 1000 GeV are 217, 5.2, 0.10 and 0.015 nanobarns, respectively. We estimate event rates by assuming design luminosity which leads to  $10^7$  events per year per nanobarn. For  $M_{\tilde{g}} = 120$  GeV there would be  $2 \times 10^9$  events per year, but the separation of these events from background would be extremely difficult. For most values of  $\mu$  there would be about  $10^9$  events in which one or both gluinos decayed directly to the LSP ( $\tilde{\chi}_1^0$ ) giving 2-4 jets plus  $E_T^{miss}$ . Unfortunately the magnitude of  $E_T^{miss}$  will not be that different from that of many backgrounds so that the Tevatron collider (where backgrounds will be much smaller) is a more logical place to search for such masses. Other signals for a 120 GeV gluino come from one gluino going directly to the LSP while the other has a 5-body decay, or from both gluinos undergoing a 5-body decay, and include:

$$q\bar{q} q\bar{q} l^+ l^- E_T^{miss}$$

$$q\bar{q} q\bar{q}' \mu^+ E_T^{miss}$$

$$q\bar{q}' q\bar{q}' \mu^+ e^+ E_T^{miss}$$

In the first two cases  $E_T^{miss}$  would be comparable to the double LSP case, whereas the latter has very little  $E_T^{miss}$ . The invariant mass of the  $l^+ l^-$  pair in the first channel would be 45-70 GeV in most cases. Again backgrounds are probably prohibitive.

For  $M_{\tilde{g}} = 300 \text{ GeV}$  the signals are very similar to those just described, but there may now be adequate  $E_T^{miss}$  to distinguish signal from background (although this requires study). For most  $\mu$  values there would be ten million events/year of the single or double LSP signature (unless  $\mu$  is very small in which case the event rate goes to zero). Our studies indicate that the  $E_T^{miss}$  spectrum from events in which one gluino goes directly to the LSP and the other gluino goes to anything is very similar to that in which both gluinos decay directly to LSP's (see Sec. 4 also). Placing a very high  $E_T^{miss}$  cut on the data leads to a suppression of 1.5 on the single-LSP case relative to the double-LSP case. But since there is a factor of 12 advantage in the branching ratio, it is the single-LSP case which is most important. The signals with leptons resulting from one or two five-body decays lead to several million events/year. Here we expect  $M(l^+l^-) = 90-100 \text{ GeV}$  for  $\mu < -50 \text{ GeV}$  and  $M(l^+l^-) = 30-70 \text{ GeV}$  for  $\mu > -50 \text{ GeV}$ . It should be emphasized that all of these signatures are expected simultaneously independent of  $\mu$  (although backgrounds may be more severe in some cases). At this gluino mass we see for the first time the possibility of the signal with W or Z in the decay products. For  $-100 < \mu < 25 \text{ GeV}$  we expect 5-20 million events/year with a W or Z, *e.g.*

$$q\bar{q} q\bar{q} q\bar{q} q\bar{q} W E_T^{miss}.$$

A better signature is presumably found from the million or so events which would contain two vector bosons. The Z contribution begins only for  $\mu > -30 \text{ GeV}$ , but can be as much as 12% of the branching ratio. For these  $\mu$  values we expect 500-2500 events/year in which two Z bosons result and both decay to lepton pairs.

For  $M_{\tilde{g}} = 700 \text{ GeV}$  the nature of the signals is somewhat different depending on the value of  $\mu$ . For  $160 < \mu < 620/\text{GeV}$ , the 5-body modes remain large at the expense of the W and Z modes, whereas for all other  $\mu$  values the W and Z modes have replaced the 5-body modes. The single and double LSP modes (one or two gluino decays directly to the LSP) lead to 300,000 events/year with substantial missing energy and 2-4 hard jets (unless  $|\mu| < 80 \text{ GeV}$ ). The number of jets depends on how many are coalesced by the jet-finding procedure. For high gluino masses (as here) we expect 3-4 jets most of the time. For  $\mu < 160 \text{ GeV}$  there will be 100,000-300,000 events with two vector bosons. However, for  $\mu < -100 \text{ GeV}$  these are always W bosons. For  $-100 < \mu < 160 \text{ GeV}$ , there will be 40-80 events/year with two Z bosons both of which decay to  $l^+l^-$ . In addition there are mixed modes where the two gluinos have different decays. One gluino may decay directly to the LSP ( $\tilde{\chi}_1^0$ ) while the other goes to a Z giving:

$$q\bar{q} q\bar{q} q\bar{q} Z E_T^{miss}.$$

Thus one would find large  $E_T^{miss}$  and a Z boson plus 3-4 hard jets. Of these events, 1500 events/year with the Z decaying to leptons would occur if  $60 < \mu < 200 \text{ GeV}$ . (In this range, branching ratios for  $\tilde{g} \rightarrow \text{LSP}$  and  $\tilde{g} \rightarrow Z$  are both sufficiently large.) Far more common would be the equivalent process with W bosons (decaying to leptons). 10,000-30,000 such

events would occur for most  $\mu$  below 200 GeV. For large positive  $\mu$  one finds events with one gluino going directly to the LSP and one having a 5-body decay. These 130,000 events would have large  $E_T^{miss}$  and very large total scalar  $E_T$ . Here, for the  $l^+l^-$  pair associated with 5-body decays, we expect  $M(l^+l^-) = 100 - 160$  GeV.

At  $M_{\tilde{g}} = 1000$  GeV the 5-body decays are relevant for only limited  $\mu$  values. The W boson modes are now substantial for all parameters, and the Z boson for  $|\mu| < 300$  GeV. However, with this large gluino mass the cross-section has dropped so that one can no longer look for events with small branching fractions. The number of events in which both gluinos decay to Z bosons (assuming  $|\mu| < 300$  GeV) and each boson decays to leptons is now only 10-15 events (although we expect backgrounds to be even smaller). The number of events/year with two W bosons each decaying leptonically is 800-3000; these events would have 3-4 jets with about 150-300 GeV each and the total scalar energy would be over 2000 GeV. There would be about 170 events with a W and a Z boson (if  $|\mu| < 300$  GeV) in which both decayed leptonically. Except for the region  $-150 < \mu < 50$  GeV, one or both gluinos could decay directly to the LSP giving 40,000 events with enormous  $E_T^{miss}$ . If the two gluinos have different decay modes, we can find 4000 events with a leptonically decaying W boson and a direct LSP (giving very high  $E_T^{miss}$ ), or 300 events with  $Z \rightarrow l^+l^-$  and the direct LSP.

In conclusion we wish to again emphasize that the discussion above is intended to indicate signatures deserving further consideration. No attempt was made here to account for backgrounds, efficiencies or cuts. Discussion of the role of the Higgs decay modes will appear in a forthcoming paper.<sup>20</sup> In the above we have assumed  $\tan \beta = 1.5$  and  $m_{H^+} = 150$  GeV. For smaller  $\tan \beta$  little change occurs. For larger  $\tan \beta$  most changes are not significant, but decays to the 5-body channels are enhanced at the expense of the Higgs decay mode. If  $m_{H^+}$  is increased, there is little overall impact except for  $M_{\tilde{g}} = 1000$  GeV, where the W and Z modes are somewhat enhanced at relatively small  $|\mu|$ . However, if  $m_{H^+}$  is reduced to 90 GeV, we see a substantial change for  $M_{\tilde{g}} > 500$  GeV. The branching fractions for the W and Z bosons modes drop by a factor of 2-3 for negative  $\mu$ , with the Higgs modes making up the difference. The impact is much smaller for positive  $\mu$ .

Finally, we can compare the ability of the SSC and the LHC to find many of the signals discussed here. This comparison<sup>12</sup> appears in table I.

Table 1

Approximate Event Rates for SSC vs. LHC

Event rates for an integrated luminosity of  $10^{40} \text{ cm}^{-2}$  from  $\tilde{g}\tilde{g}$  production, before cuts and efficiencies. Rates are given for those regions of  $\mu$  where a given signal is most significant. These  $\mu$  regions are indicated (in  $\text{GeV}$  units) by the parentheses. Note that there is always a gap in  $\mu$  (near  $\mu = 0$ ) due to our elimination of  $\mu$  values for which  $M_{\tilde{\chi}_1^+} < 30 \text{ GeV}$ . We assume  $\sqrt{s} = 40 \text{ TeV}$  and  $\sqrt{s} = 17 \text{ TeV}$  for the SSC and LHC, respectively.

Signal	$M_{\tilde{g}} = 300 \text{ GeV}$	$M_{\tilde{g}} = 700 \text{ GeV}$	$M_{\tilde{g}} = 1000 \text{ GeV}$
1 direct LSP+any; $\Rightarrow$ jets+ $E_T^{\text{miss}}$	$10^7$ vs. $10^6$ $(-\infty, -40); (160, \infty)$	$3 \times 10^5$ vs. $2 \times 10^4$ $(-\infty, -100); (70, \infty)$	$4 \times 10^4$ vs. <b>1700</b> $(-\infty, -140); (60, \infty)$
Two 5-body decays with leptons	$10^7$ vs. $10^6$ $(-\infty, 30); (160, \infty)$	<b>6000</b> vs. <b>400</b> $(70, 620)$	<b>240</b> vs. <b>10</b> $(200, 300)$
Two $Z$ 's; $Z \rightarrow l^+l^-$	<b>1000</b> vs. <b>100</b> $(-40, 30)$	<b>50</b> vs. <b>3</b> $(-200, 0); (70, 200)$	<b>10</b> vs. <b>0.4</b> $(-300, -10); (60, 250)$
$Z$ + direct LSP; $Z \rightarrow l^+l^-$	<b>100</b> vs. <b>14</b> $(-40, 30)$	<b>2000</b> vs. <b>130</b> $(-200, -100); (70, 200)$	<b>300</b> vs. <b>13</b> $(-300, -140); (60, 300)$
5-body+direct LSP; 5-body $\rightarrow$ leptons	$10^6$ vs. $10^5$ $(-\infty, -40); (160, \infty)$	<b>20,000</b> vs. <b>1400</b> $(-180, -100); (70, 620)$	<b>1500</b> vs. <b>60</b> $(100, 300)$
$W$ + direct LSP; $W \rightarrow$ leptons	$5 \times 10^5$ vs. $8 \times 10^4$ $(-100, -70)$	<b>20,000</b> vs. <b>1400</b> $(-\infty, -100); (70, 250)$	<b>4000</b> vs. <b>170</b> $(-\infty, -140); (60, \infty)$
$W + Z$ ; $W, Z \rightarrow$ leptons.	$3 \times 10^4$ vs. $4 \times 10^3$ $(-40, 30)$	<b>1000</b> vs. <b>70</b> $(-200, 0); (70, 200)$	<b>200</b> vs. <b>8</b> $(-300, -140); (60, 300)$

### 3. Squark Decays

The assumptions made for the squark analysis are very similar to those made for the gluino analysis. The results discussed here are described in greater detail in Ref. 13 which also appears in these proceedings. Here of course we choose  $M_{\tilde{q}} < M_{\tilde{g}}$ . For definiteness in the results quoted, it was assumed that  $M_{\tilde{g}} \approx M_{\tilde{q}}$ . Some such assumption is essential since it fixes the relationship between  $M_{\tilde{q}}$  and the parameter  $M$  (see eqn. (3)). It was checked that the conclusions remain qualitatively the same if a larger  $M_{\tilde{g}}$  is chosen. In this section as in the gluino section, we will ignore  $\tilde{q}\tilde{g}$  production and concentrate on  $\tilde{q}\tilde{q}$  production.

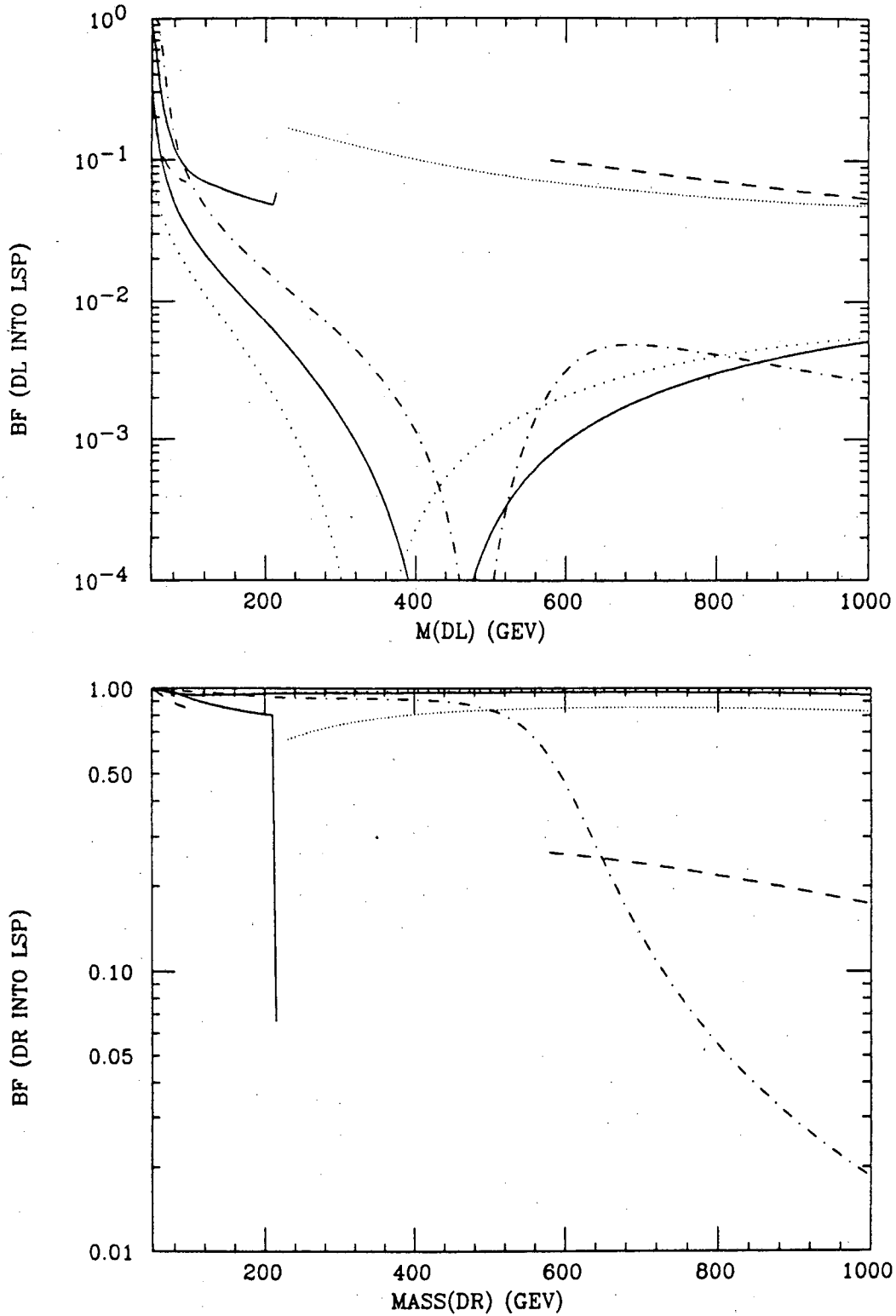
Consideration of squarks is somewhat more complicated than that of gluinos since there are two flavors (“up” and “down”) and since there are supersymmetric partners of the left-handed quarks ( $\tilde{q}_L$ ) and partners of the right-handed quarks ( $\tilde{q}_R$ ). (Other flavors are treated as being the same as u and d). Furthermore the cross-section for  $\tilde{q}_L\tilde{q}_L$  production (or  $\tilde{q}_R\tilde{q}_R$  production) is not the same as that for  $\tilde{q}_L\tilde{q}_R$ . When  $M_{\tilde{q}} < M_{\tilde{g}}$ , then the following two-body decays will dominate (if they are kinematically allowed):

$$\tilde{q}_L \rightarrow q'_L \tilde{\chi}_i^\pm \quad (12)$$

$$\begin{aligned} \tilde{q}_L &\rightarrow q_L \tilde{\chi}_i^0 \\ \tilde{q}_R &\rightarrow q_R \tilde{\chi}_i^0 \end{aligned} \quad (13)$$

where  $i=1,2$  for  $\tilde{\chi}_i^\pm$  and  $i=1,2,3,4$  for  $\tilde{\chi}_i^0$ . Note that there are no couplings of  $\tilde{q}_R$  to  $\tilde{\chi}_i^\pm$  for the same reason that  $q_R$  do not couple to  $W$  bosons. The branching ratios of all these modes can be found in Ref. 10. These papers and fig. 9 show that left-handed squarks with mass  $M_{\tilde{q}} > 150 \text{ GeV}$  rarely decay directly to the LSP ( $\tilde{\chi}_1^0$ ). However, the dominant decay of right-handed squarks is directly to the LSP if  $|\mu| \gtrsim M_{\tilde{q}}/3$ . When this condition is obeyed, the heavier neutralinos are dominated by their higgsino components (or by their neutral  $SU(2)$  gaugino components) and therefore have a very small coupling to squarks.

The decays of the charginos and neutralinos (produced in squark decay) were discussed in the previous section. As for gluinos one of the products of cascading decays are  $W$  and  $Z$  bosons. In fig. 10 (from ref. 13) we show the branching fractions for the various types of squarks into real  $W$  and  $Z$  bosons. For the case  $\mu \lesssim M_{\tilde{q}}/3$  ( $= M_{\tilde{g}}/3$ ) we see that left-handed squarks have branching ratios into  $W$  and  $Z$  bosons of 50% and 20%, respectively. Right-handed squarks of course have a small (3%) branching ratio to  $W$  and  $Z$  bosons, since they usually decay directly to the LSP. With design luminosity we expect about  $8 \times 10^5$   $\tilde{q}_L\tilde{q}_L$  pairs annually at the SSC if  $M_{\tilde{q}} = 0.5 \text{ TeV}$  or  $4 \times 10^4$  pairs if  $M_{\tilde{q}} = 1 \text{ TeV}$ . We now find (for  $|\mu| \lesssim M_{\tilde{q}}/3$ ) that the number of events in which both squarks have a cascade decay yielding a  $Z$  boson and both of the resulting  $Z$  bosons decay to  $l^+l^-$ , is 120 per year for  $M_{\tilde{q}} = 0.5 \text{ TeV}$  and 6 events per year if  $M_{\tilde{q}} = 1 \text{ TeV}$ . These events would contain two hard jets from the primary decay in addition to the two leptonically decaying  $Z$  bosons.



**Figure 9:** The branching ratios for direct decays of  $\tilde{d}_L$  and  $\tilde{d}_R$  to the LSP as a function of  $M_{\tilde{q}}$  (with  $M_{\tilde{q}} = M_{\tilde{d}}$ ) for  $\mu = -3m_W$  (close dots),  $-m_W$  (dashed),  $-m_W/2$  (solid ending at 200 GeV),  $m_W$  (dot-dashed),  $2m_W$  (solid continuing past 200 GeV), and  $3m_W$  (dotted) at  $\tan\beta = 1.5$ . As in previous figures, omitted portions of the curves correspond to parameter regions where  $M_{\tilde{\chi}_1^+} < 30$  GeV.



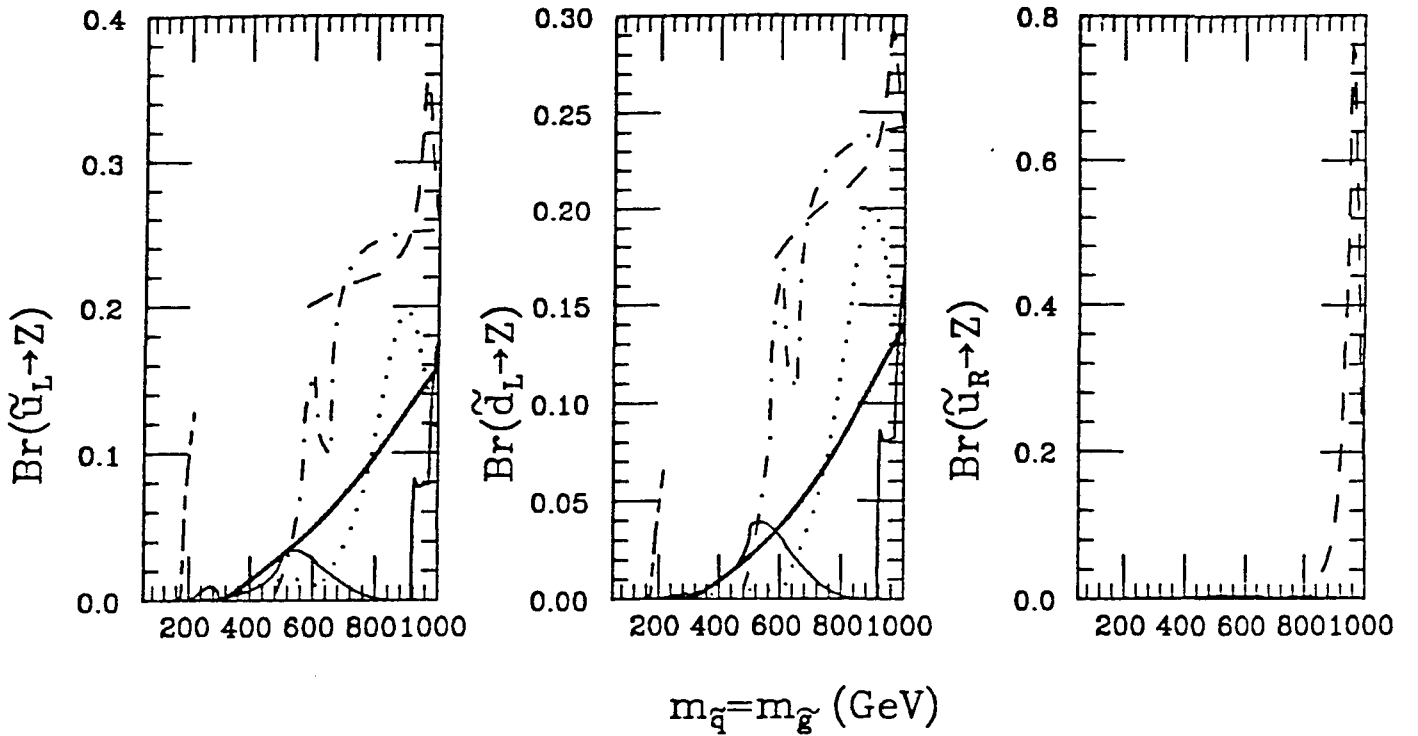


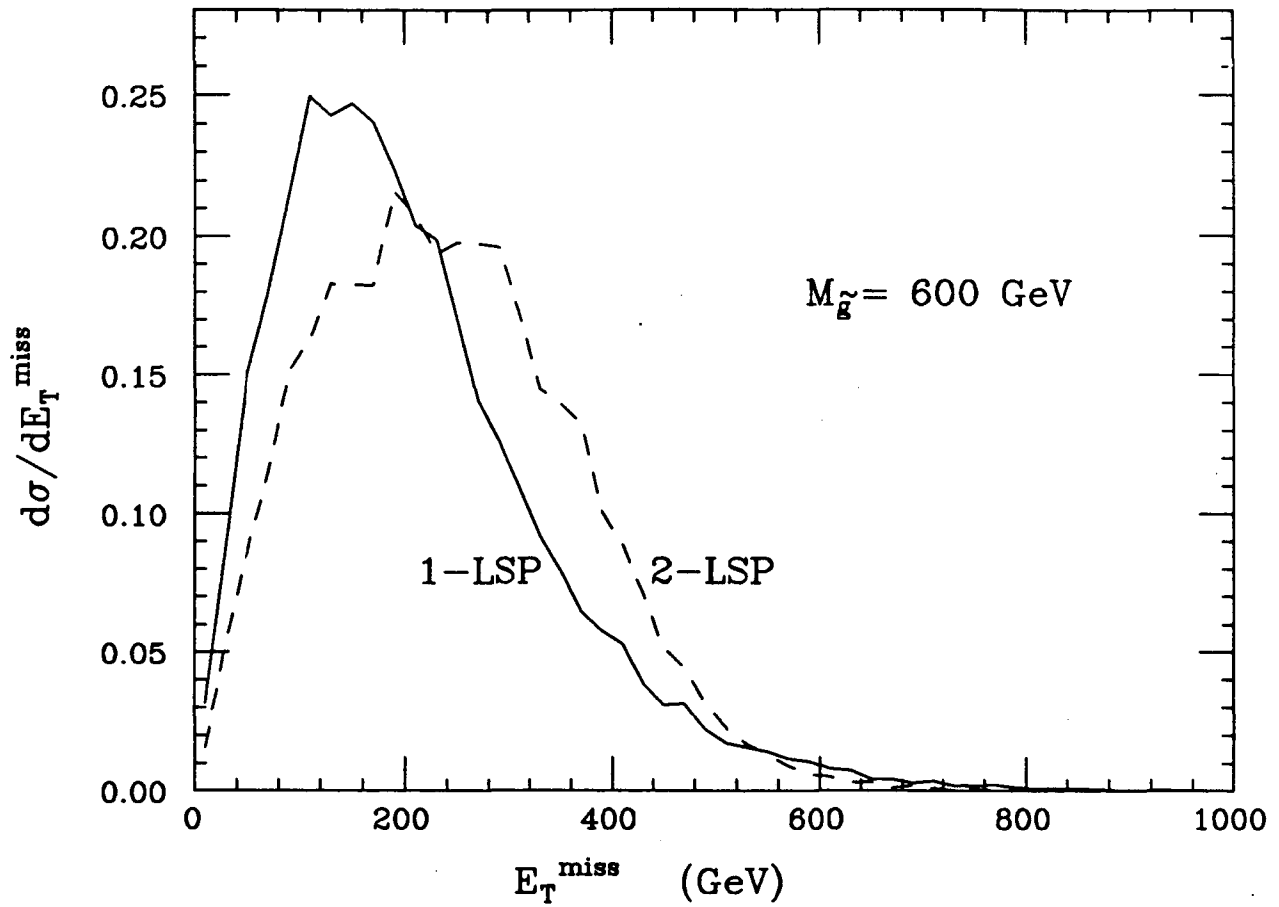
Figure 10: The squark branching ratios to  $W$  and  $Z$  as a function of  $M_{\tilde{q}}$  (with  $M_{\tilde{q}} = M_{\tilde{g}}$ ) for  $\mu = -3m_W$  (thick solid),  $-m_W$  (long dashed),  $-m_W/2$  (long-short dashed),  $m_W$  (dot-dashed),  $2m_W$  (solid), and  $3m_W$  (dotted) at  $\tan\beta = 1.5$ . As in previous figures, omitted portions of the curves correspond to parameter regions where  $M_{\tilde{\chi}_1^+} < 30 \text{ GeV}$ .

#### 4. Direct Decays of Gluinos and Squarks to the LSP

When most people think of supersymmetry, it is the jets plus large missing energy signal which comes to mind (where the missing energy originates in LSP's coming from decays of the gluinos or squarks). However, we have shown that the maximum branching ratio for direct decay of gluinos to the LSP ranges from 13 to 20% for masses of interest at the SSC. Therefore, in  $\tilde{g}\tilde{g}$  production only 2 to 4% of the events have both gluinos decaying directly to the LSP. As discussed previously, this motivates us to look at the "single-LSP" case (where only one of the LSP's has decayed directly to the LSP). As seen in Fig. 11 the spectra for the "single-LSP" and "double-LSP" cases are very similar and therefore the required  $E_T^{miss}$  cut will not substantially reduce the single-LSP case relative to the double-LSP case (only by a factor of about 1.5). Since the branching ratio for the single-LSP case is 8-12 times larger, one needs to study the single-LSP case in greater detail (unfortunately this has not yet been done). Turning to squarks, it is only  $\tilde{q}_R$  which have substantial direct decays to the LSP, so that in  $\tilde{q}\tilde{q}$  production only  $\tilde{q}_R\tilde{q}_R$  contributes to the case where both squarks decay directly to an LSP. And even  $\tilde{q}_R$  do not have large LSP branching fractions for all  $\mu$  and  $M_{\tilde{q}}$ . In the following we assume that one would only consider production of pairs of the lighter of  $\tilde{g}$  and  $\tilde{q}$ .

In the time available for this workshop we have not been able to perform a detailed, high-statistics study of  $\tilde{g}\tilde{g}$  and  $\tilde{q}\tilde{q}$  production at the SSC which would take into account the small branching ratios to the LSP. We report only the results of a limited study of  $\tilde{g}\tilde{g}$  performed with ISAJET. However, we refer the reader to an excellent study done for the LHC project by R. Batley<sup>21</sup> (which however did not account for a small branching ratio or for the case where only one gluino decayed directly to the LSP). In Batley's work the signals from  $\tilde{g}\tilde{g}$  and  $\tilde{q}\tilde{q}$  production and the backgrounds from semi-leptonic heavy flavor decays and from weak vector boson production are evaluated with very high statistics using the ISAJET Monte Carlo program (version 5.25). In his study the LHC energy was taken to be  $\sqrt{s} = 17 TeV$  and  $M_{\tilde{g}}$  and  $M_{\tilde{q}} = 600 - 1000 GeV$  were considered. The backgrounds were dominated by  $t\bar{t}$  events with  $t$  decaying semi-leptonically ( $m_t = 40$  and  $200 GeV$  were considered). In calculating QCD jet production, ISAJET uses only the leading-order  $2 \rightarrow 2$  matrix elements, but initial-state and final-state radiation is included.

The  $t\bar{t}$  pair can be produced in the original hard scattering ("direct") or can occur in the evolution of one of the two gluon jets of the original hard scattering ("indirect"). Although direct production is 10-30 times larger than indirect, the indirect production is far more efficient at passing an  $E_T^{miss}$  cut so that the direct mode ends up being comparable to indirect. To pass a large  $E_T^{miss}$  cut presumably requires both  $t$  and  $\bar{t}$  to undergo a semi-leptonic decay and requires both of the resulting neutrinos to go the in same direction (otherwise the missing energy cancels). In direct production the  $t$  and  $\bar{t}$  tend to go in opposite directions whereas in indirect production both  $t$  and  $\bar{t}$  tend to go opposite the gluon.



**Figure 11:** The  $E_T^{\text{miss}}$  spectra for  $\tilde{g}\tilde{g}$  production ( $M_{\tilde{g}} = 600 \text{ GeV}$ ) where one or two of the gluinos decay as  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$  (where  $\tilde{\chi}_1^0$  is the LSP). The double-LSP case has units of  $\text{pb}/\text{GeV}$  while the single-LSP case is normalized to have the same area.

Batley used several techniques to reduce backgrounds. First, events containing muons with  $p_T^\mu > 15 \text{ GeV}/c$  were removed. Similarly, events containing an *isolated* electron passing this cut were eliminated. “Isolated” was defined as

$$\Sigma p_T^{\text{hadron}}(\Delta R < 0.4) / p_T^e < 0.1 \quad (14)$$

where  $(\Delta R)^2 = (\Delta\eta)^2 + (\Delta\phi)^2$ . These cuts are quite effective in removing backgrounds involving  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$ . They also remove more than 50% of the  $t\bar{t}$  background and are especially effective as the  $t$  mass increases. However, one should note that roughly half of gluino decays to the LSP contain heavy quarks ( $\tilde{g} \rightarrow c\bar{c}\tilde{\chi}_1^0$ ,  $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$  and  $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ ). In comparison,  $\tilde{u}$  and  $\tilde{d}$  account for about 80% of all squark production.

A second technique for reducing backgrounds is the elimination of events with small jet multiplicities. For  $M_{\tilde{g}}$  or  $M_{\tilde{q}} = 1 \text{ TeV}$  Batley chose  $E_T^{\text{jet}} > 250 \text{ GeV}$ . With this definition of a jet, the background jet multiplicity peaks sharply at 1 jet, while squarks and gluinos peak at 2 jets and in fact about 40% of gluino events have 3 or more jets. This cut is most effective at eliminating the  $g + Z$  ( $Z \rightarrow \nu\bar{\nu}$ ) background, although this effectiveness is reduced as the  $E_T^{\text{miss}}$  cut is placed very high.

Finally there are several possible event topology cuts related to the angles among the various jets and between jets and the missing energy vector. Batley listed five variables:

1.  $\Delta\phi$ , the azimuthal angle between  $E_T^{\text{miss}}$  and  $p_T^{\text{leading jet}}$ .
2.  $\Delta\phi_{12}$ , the azimuthal angle between the two jets with the highest  $p_T$ .
3. Circularity  $C = \frac{1}{2} \min(\Sigma E_T \hat{n})^2 / (\Sigma E_T^2)$  where the sum is over calorimeter cells and where the minimization is over all  $\hat{n}$  (a unit vector in the transverse plane).  $C = 0$  gives pencil-like events and  $C = 1$  give isotropic events.
4.  $x_{\text{out}} = (E_T^{\text{miss}} \sin(\Delta\phi_c)) / E_T^{\text{total}}$  where  $\Delta\phi_c$  is the azimuthal angle between  $E_T^{\text{miss}}$  and  $\hat{n}_{\text{min}}$ .
5.  $\Delta\phi_n$ , the azimuthal angle between  $E_T^{\text{miss}}$  and  $p_T^{\text{closest jet}}$  where the closest jet means closest in azimuth and requires  $P_T^{\text{jet}} > 50 \text{ GeV}$ .

Not all of these cut variables were used, in part, because even with the enormous statistics used in Batley’s study, it would have become difficult to generate any events (especially for the  $t\bar{t}$  backgrounds which unfortunately are the largest backgrounds). He therefore commented that it was likely that backgrounds could be further reduced. His results were presented in a table and included the assumption that the branching fractions for gluino and squark decays directly to the LSP were 100%. To give the reader a rough idea of the impact of branching ratios on Batley’s analysis we have multiplied his gluino rates by 0.26 ( $= 2 \times 0.14 - 0.14^2$  since either gluino can decay to an LSP) with the crude assumption that there would have been no difference in his analysis if he had studied the single-LSP case instead of the double-LSP case. We show in Table 2 a small portion of his table comparing the gluino signal with backgrounds.

Table 2

Event Rates after Selection Cuts  
including Branching Ratio of  $\tilde{g} \rightarrow LSP$

Event rates for an integrated luminosity of  $10^{40} \text{ cm}^{-2}$  from various backgrounds and  $\tilde{g}\tilde{g}$  production, after the following cuts:  $p_T^{jet} > 250 \text{ GeV}$ ,  $N_{jet} \geq 3$ ,  $E_T^{miss} > 500 \text{ GeV}$  and circularity  $C > 0.25$ . Events with identified muons and isolated electrons were eliminated (see text). The LHC energy was taken as  $\sqrt{s} = 17 \text{ TeV}$ . These results were taken from Ref. 21, but the gluino numbers have been multiplied by the branching ratio 0.26.

Process	Number of Events
QCD ( $m_t = 40 \text{ GeV}$ )	167 ± 48
QCD ( $m_t = 200 \text{ GeV}$ )	64 ± 17
$Z \rightarrow \nu\bar{\nu}$	7 ± 2
$W \rightarrow \tau\nu$	7 ± 2
other	3 ± 1
total bgd. ( $m_t = 40 \text{ GeV}$ )	184 ± 48
total bgd. ( $m_t = 200 \text{ GeV}$ )	80 ± 17
$\tilde{g}\tilde{g}$ ( $M_{\tilde{g}} = 600 \text{ GeV}$ )	494 ± 143
$\tilde{g}\tilde{g}$ ( $M_{\tilde{g}} = 800 \text{ GeV}$ )	403 ± 52
$\tilde{g}\tilde{g}$ ( $M_{\tilde{g}} = 1000 \text{ GeV}$ )	195 ± 26
$\tilde{g}\tilde{g}$ ( $M_{\tilde{g}} = 1500 \text{ GeV}$ )	26 ± 1.3

Clearly further analysis of cuts would be required for the higher  $M_{\tilde{g}}$  in order to get an acceptable signal to background ratio. The event rates shown are for the LHC ( $\sqrt{s} = 17 \text{ TeV}$ ); at the SSC the signal would be increased by a factor of more than 10 (for the gluino masses given) while the background would increase at a somewhat slower rate (about a factor of 4 conservatively estimated, see Ref. 22.) We have not calculated the impact of branching ratios on Batley's results for squarks (we note, however, that he chose to study the worse case scenario in which the gluino is extremely heavy and in which squark-gluino scattering is ignored).

From the above discussion we have learned that severe cuts are needed to eliminate backgrounds. Unfortunately with these cuts, such a large fraction of the Monte Carlo generated background is eliminated that with plausible numbers of events generated, one frequently

finds that no events have passed the cuts. Despite this, the resulting upper limits on the background rate can still be considerably larger than the expected signal. Of course the signal is not a problem since many signal events pass the cuts.

Work done in our subgroup (by Chris Klopfenstein) examined these same questions at SSC energies (compared with Batley's work which was at LHC energies) for the case of  $\tilde{g}\tilde{g}$  production where  $M_{\tilde{g}} = 300$  or  $600$  GeV. As mentioned above, in the time available for this workshop we have not been able to perform a detailed, high-statistics study. As was the case for Batley, this study examined the case in which both gluinos decayed directly to the LSP. We outline below the procedure which was followed:

1. Events were generated using ISAJET version 5.34.
2. A crude calorimeter simulation was used assuming perfect calorimetric coverage over  $|\eta| < 5$  and all  $\phi$ . Segmentation in  $\eta$  and  $\phi$  was 0.05/cell. Smearing of energy with Gaussian resolution was taken to be:

$$\begin{aligned} (\sigma/E)^2 &= (0.15/\sqrt{E})^2 + (0.01)^2 && \text{for EM energy} \\ (\sigma/E)^2 &= (0.35/\sqrt{E})^2 + (0.01)^2 && \text{for hadronic energy.} \end{aligned} \tag{15}$$

3. Jets were found using the following algorithm (which is part of the ISAJET package): Find the cell with the highest  $E_T$ . If this exceeds  $E_{cut}^{cell}$  ( $= 5$  GeV), then continue and include in this jet all cells within  $\Delta R < R_{jet}$  ( $= 1.$ ) with  $E_T^{cell} > E_T^0$  ( $= 1$  GeV). If the resulting  $E_T^{jet}$  has  $E_T^{jet} > E_{cut}^{jet}$  ( $= 20$  GeV), then keep the jet. This procedure is then repeated but ignoring all cells now in a jet.
4. Finally we applied a number of cuts to these events:
  - $N_{jets} \geq 3.$
  - $\Delta\phi < 150$  degrees (see Batley's definition (1) above).
  - $E_T^{miss} > M_{\tilde{g}}/2.$
  - $E_T^{jet} > 50$  GeV.

The results of our study of  $\tilde{g}\tilde{g}$  production in which both gluinos decay directly to the LSP are summarized in Table 3. In order to give the reader an idea of the impact of the single-LSP mode, the  $\tilde{g}\tilde{g}$  cross sections have been multiplied by the branching ratios appropriate for the single-LSP mode (where only one of the gluinos has decayed directly to an LSP) instead by the branching ratios squared. The cross sections shown are obtained by summing separate ISAJET runs for different  $p_T$  ranges of the initial  $2 \rightarrow 2$  processes. Each of these runs contained 10,000 to 40,000 events; however, for backgrounds there were often no events passing the cuts. When the initial cross sections were large, the resulting cross section limits after cuts were sometimes quite substantial despite having no events. The upper limits in Table 3 occur when  $p_T$  bins with no events are included. The lower limits occur when it is assumed that bins with no events make no contribution to the cross section.

**Table 3**

**Signal and Background Cross Sections  
including Branching Ratio of  $\tilde{g} \rightarrow LSP$**

Cross sections times branching ratios ( $2 \times 0.2 - 0.2^2$  for  $M_{\tilde{g}} = 300 \text{ GeV}$  and  $2 \times 0.14 - 0.14^2$  for  $M_{\tilde{g}} = 600 \text{ GeV}$ ) from  $\tilde{g}\tilde{g}$  production and various backgrounds after the four cuts shown in text; the first box below uses  $E_T^{miss} > 150 \text{ GeV}$  whereas the second has  $E_T^{miss} > 300 \text{ GeV}$ . Events with muons and electrons were *not* eliminated. The SSC energy was taken as  $\sqrt{s} = 40 \text{ TeV}$ .

Process	Cross Section (pb)
$gg (m_t = 70 \text{ GeV})$	$419 > \sigma > 239 \pm 86$
$t\bar{t} (m_t = 70 \text{ GeV})$	$16 \pm 2$
$Z \rightarrow \nu\bar{\nu}$	$0.5 \pm 0.1$
$W \rightarrow \tau\nu$	$1 \pm 0.2$
total bgd. ( $m_t = 70 \text{ GeV}$ )	$436 > \sigma > 256 \pm 86$
$\tilde{g}\tilde{g} (M_{\tilde{g}} = 300 \text{ GeV})$	$261 \pm 9$

Process	Cross Section (pb)
$gg (m_t = 70 \text{ GeV})$	$234 > \sigma > 1.5 \pm 0.3$
$t\bar{t} (m_t = 70 \text{ GeV})$	$5.9 > \sigma > 0.3 \pm 0.2$
$Z \rightarrow \nu\bar{\nu}$	$0.15 > \sigma > 0.03 \pm 0.01$
$W \rightarrow \tau\nu$	$0.39 > \sigma > 0.03 \pm 0.02$
total bgd. ( $m_t = 70 \text{ GeV}$ )	$241 > \sigma > 1.8 \pm 0.5$
$\tilde{g}\tilde{g} (M_{\tilde{g}} = 600 \text{ GeV})$	$1.8 \pm 0.07$

Clearly even when the lower limits are used, the signal to background ratios with this limited set of cuts are not yet adequate. Note, however, that if the branching-ratio for  $\tilde{g} \rightarrow LSP$  had been taken as 100% (as in previous studies), the signal would have been four times larger. The real problem with these analyses is that the cuts we used were inadequate (did not separate signal and background sufficiently) and yet we had difficulty generating enough background events so that a few events passed the cuts. Once we choose a stronger

set of cuts the problem will be magnified. This situation has resulted from the fact that the signal cross sections have decreased by a factor of 3-4, necessitating more severe cuts. A complete study with very high statistics is needed to gain any real insight into this problem. Such a study should focus on the single-LSP case where only one of the gluinos decays directly to the LSP.

## 5. Decays of Gluinos and Squarks to W and Z Bosons

We have shown in Sec. 2 that heavy gluinos and squarks ( $M_{\tilde{g}} > 300 \text{ GeV}$ ) have substantial probabilities for cascade decays resulting in W or Z bosons. However, the important question is whether or not a clear signal can be identified and whether there are large backgrounds. The problem is, of course, greater with W bosons even though there are roughly twice as many W bosons as Z bosons and even though the leptonic decay modes of W bosons are about three times those of Z bosons. We have therefore focussed on events in which both gluinos have decayed into Z bosons and both Z bosons have decayed to either  $e^+e^-$  or  $\mu^+\mu^-$ . Preliminary discussion of these questions first appeared in Ref. 19 where a number of figures were shown which displayed a variety of distributions for the signal. Similar distributions for squarks decaying to Z bosons were shown in Ref. 13 which appears in these proceedings. We do not have the space here to reproduce either set of figures, but we will summarize the conclusions. Other signatures are as useful as these but in the time available for this workshop were not considered.

In the work of Ref. 19 and in work reported here, we have examined the signal in which both gluinos have the decays:

$$\begin{aligned}\tilde{g} &\rightarrow q\bar{q}\tilde{\chi}_i \\ \tilde{\chi}_i &\rightarrow \tilde{\chi}_j Z \\ Z &\rightarrow l^+l^-\end{aligned}\tag{16}$$

The final-state from  $\tilde{g}\tilde{g}$  production and decay is therefore  $qq\bar{q}\bar{q} l^+l^-l^+l^-$  plus additional particles from the decays of the two remaining  $\tilde{\chi}_j$ . Thus, the signature is 4 or more hard jets plus two Z bosons. We have examined two cases:  $M_{\tilde{g}} = 500 \text{ GeV}$  and  $M_{\tilde{g}} = 750 \text{ GeV}$ . We find that typically two of the jets are especially hard (more than 100-200 GeV). A third jet has at least 60-70 GeV. The total scalar energy coming from the three leading jets plus the two Z bosons is greater than 600-700 GeV.

Our studies indicate that the largest backgrounds for this signal is likely to be from the processes: a)  $pp \rightarrow gq\bar{q}$  (or  $gqq$ ) where each quark then radiates a Z boson, b)  $pp \rightarrow ZZ$  where three additional jets occur as initial-state radiation and c)  $pp \rightarrow qZ$  where the quark radiates a Z boson and two additional jets occur as initial-state radiation. (These three processes are not really unrelated, of course). We will show the first two backgrounds to be small and assume by analogy that the third is small. Starting with process b), we have calculated the signal and this background using ISAJET 5.34 and Pythia 4.9 (this work was done by Edward Wang).  $ZZ$  production was calculated with  $p_T > 40 \text{ GeV}$ . The cuts



employed follow from the discussion in the previous paragraph and for  $M_{\tilde{g}} = 750 \text{ GeV}$  ( $500 \text{ GeV}$ ) were:

- $E_T^{\text{leading jet}} > 200 \text{ GeV}$  ( $150 \text{ GeV}$ ).
- $E_T^{\text{second jet}} > 150 \text{ GeV}$  ( $100 \text{ GeV}$ ).
- $E_T^{\text{third jet}} > 70 \text{ GeV}$  ( $60 \text{ GeV}$ ).
- $E_T^{\text{total scalar}} > 700 \text{ GeV}$  ( $600 \text{ GeV}$ ).
- $\phi^{\text{leading jet}} - \phi^{\text{second jet}} < 170 \text{ deg.}$

In doing this calculation it was assumed that  $M_{\tilde{\chi}_i} = 200 \text{ GeV}$ ,  $M_{\tilde{\chi}_j} = 80 \text{ GeV}$ , and  $M_{\tilde{\chi}_1^0} = 20 \text{ GeV}$ . The Z bosons had perfect identification and reconstruction (for signal and background), the calorimetry was perfect out to  $|\eta| < 5.5$ , calorimeter granularity was  $\Delta\phi = \Delta\eta = 0.05$ , jet size was  $\Delta R < 1$  and  $E_T^{\text{jet}} > 25 \text{ GeV}$  was used.

Wang then found that the signal was 70-80% efficient at passing the cuts while only a tiny part of the background passed. Using the results of Sec. 2, we took the branching ratio of gluinos decaying to Z bosons to be 15% for  $M_{\tilde{g}} = 750 \text{ GeV}$  and 10% for  $M_{\tilde{g}} = 500 \text{ GeV}$ . The number of events per year (integrated luminosity of  $10^{40} \text{ cm}^{-2}$ ) containing 3 jets + 2 Z bosons and passing the above cuts were:

	$M_{\tilde{g}} = 750 \text{ GeV}$	$M_{\tilde{g}} = 500 \text{ GeV}$
Signal	56 events	166 events
Background (b)	$0.5 \pm 0.3$ events	$2.2 \pm 1.0$ events

where background (b) is defined above. Clearly this background is not important. We should point out that there is an additional cut which we did not employ which we found would remove all the remaining background events generated with little impact on the signal. This variable is the total scalar transverse energy in the events (not just the three jets and two Z bosons). Since we had very few events surviving the above cuts (and no additional cuts were needed), we decided not to use this cut. This cut is effective because the signal involves the production of very heavy particles and because we ignored some of the decay products in the signal. One should be able to make use of the invariant mass of the three jets plus two Z bosons to make an estimate of gluino mass should such a signal be observed.

Turning to background (a), we are not able to perform an ISAJET calculation equivalent to the one done for background (b), since ISAJET does not radiate Z bosons from jets. We can use two techniques to estimate this background. The crudest method is to argue that background (a) is closely related to background (b) but the direct production of two Z bosons (background (b)) requires both incoming partons to be quarks whereas the direct production of a gluon and two quarks (or antiquarks) can originate in gluon scattering. This gives a factor of ten advantage to background (b), but (looking at the above table) we can afford that factor. If needed, the cuts employed could have been improved. The second method to estimate background (a) was to use a parton Monte Carlo program with a  $2 \rightarrow 3$

squared matrix element for gluon-quark-quark production (provided by Ian Hinchliffe). In this program we employ the cuts described above. The results generated, of course, ignore the production of the two Z bosons. The additional effect of the radiation of transversely polarized Z bosons can then be estimated using the following factor for each radiation:

$$(g_L^2 + g_R^2) \frac{\alpha \ln \hat{s}/M_Z^2}{4\pi \sin \theta_W \cos \theta_W} f(x)$$

where  $x$  is  $p_Z/p_{quark}$  and  $f(x)$  is a calculable function. This factor (squared) together with the output of the Monte Carlo program yields  $1.3 f(x)^2$  events per year using the cuts for  $M_{\tilde{g}} = 750 \text{ GeV}$ . While a full calculation has not been done, the function  $f(x)$  is not likely to be large (especially when appropriate cuts are applied to the Z bosons). It therefore appears that there is no significant background to the signal in which both gluinos decay to Z bosons (plus other particles).

The work of Ref. 13 finds distributions similar to those described for gluinos. They conclude that for relatively small values of  $\mu$ , one would expect 120 events/year for  $M_{\tilde{g}} = 500 \text{ GeV}$  and 6 events/year for  $M_{\tilde{g}} = 1000 \text{ GeV}$ .

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