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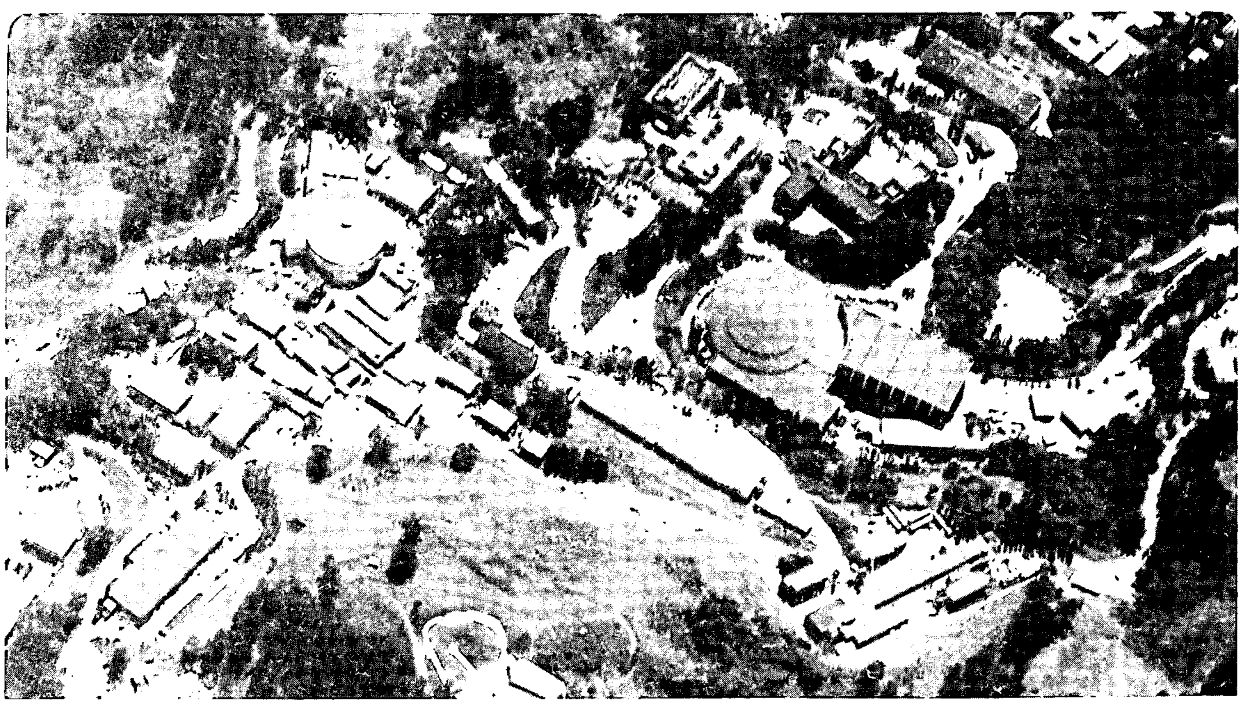

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Finding Gluinos at Hadron Colliders*

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Abstract

In the minimal supersymmetric model, we show that the branching ratio for a heavy gluino ($M_{\tilde{g}} \gtrsim 600\ GeV$) to decay directly into the lightest supersymmetric particle is less than 14%, independent of nearly all parameter assumptions. Thus, the traditional $jets + E_T^{miss}$ signature is substantially reduced. We describe the results of a comprehensive survey of search strategies as a function of the supersymmetric parameter space, and identify those which are most promising. We consider a range of gluino masses appropriate to both existing and future colliders.

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Supersymmetry is a leading candidate for new physics which will be probed by present and future colliders. At a hadron collider the supersymmetric particles directly produced via the strong interactions are the gluinos and squarks. We focus here on gluinos that are lighter than squarks, and study direct gluino production and decay. In order to examine the possible gluino signatures, we survey gluino decay patterns and their corresponding branching ratios. A more comprehensive analysis can be found in ref. 1, and early partial results are contained in ref. 2. The alternative case with squarks lighter than gluinos will be considered elsewhere.

In gluino searches at the CERN $Sp\bar{p}S$, it was tacitly assumed that the gluino decays with 100% branching ratio via $\tilde{g} \to q\bar{q}\tilde{\gamma}$. The $\tilde{\gamma}$, assumed to be the lightest supersymmetric particle (LSP), would have escaped the detector, resulting in events with jets and substantial E_T^{miss}. For a heavier gluino, the assumption of a 100% branching ratio directly into the LSP is not correct.[3] Other three-body decay modes (involving heavier neutralinos and charginos) become dominant. In this paper, we demonstrate that (given only a few simple assumptions) the branching ratio for the direct decay of gluino into the LSP is never larger than 40% (20%) for $M_{\tilde{g}} = 200$ (400) GeV, respectively, and asymptotes to 14% for $M_{\tilde{g}} \gtrsim 600\ GeV$. Thus, in the production of $\tilde{g}\tilde{g}$, the simultaneous decay of both gluinos directly into the LSP accounts for less than 2% of the total gluino event rate, at large $M_{\tilde{g}}$. However, we have found that the magnitude of the resulting missing energy is very similar if only one gluino decays directly to the LSP, while the associated branching ratio is of order 24%. Clearly, previous studies have significantly overestimated and misconstrued the nature of the traditional $jets + E_T^{miss}$ signal. Furthermore, we find that there are many other important signatures which can provide substantial evidence for gluino production. These other signatures also yield significant information regarding the neutralinos and charginos of the supersymmetric theory. In particular, these signatures arise when the heavier neutralinos and charginos undergo two-body decays to W, Z or Higgs bosons or three-body decays such as to l^+l^- + LSP.

We have chosen to focus on the minimal supersymmetric extension of the Standard Model, specified in detail in refs. 4 and 5. In this model the spin-1/2 superpartners of the two Higgs doublets combine with the superpartners of the $W^\pm$ and of the γ,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 lightest neutralino, $\tilde{\chi}_1^0$, is taken to be the LSP. In the minimal supersymmetric model the mass matrices for the $\tilde{\chi}^\pm$ and $\tilde{\chi}^0$ sectors depend on three unknown mass scales—μ, M_2, and M_1—in addition to the Higgs vacuum expectation values to be discussed shortly. Here μ 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, by requiring that the three mass scales are equal at some grand unification scale. Using the notation of refs. 4 and 5, where $M_2 \equiv M$ and $M_1 \equiv$

$(3/5)M'$, this requirement implies $M = (g^2/g_s^2)M_3$ and $M' = (5g'^2/3g_s^2)M_3$. The gluino mass is given by $M_{\tilde{g}} = |M_3|$. Not all values of the parameters are experimentally allowed. In fact, for a given $M_{\tilde{g}}$ there is always a region of μ for which the mass of the lightest chargino is less than the experimental lower bound which we take to be $\sim 30\ GeV$. In what follows we shall only present results for μ values that do not violate this bound.

Because the heavier neutralinos and charginos can decay to a Higgs boson, we briefly review the Higgs sector of the minimal supersymmetry model, using the notation of ref. 5. 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. There are three neutral Higgs ($H^0_{1,2,3}$) and a charged pair ($H^\pm$). One finds that by fixing $\tan\beta \equiv v_2/v_1$ and one of the Higgs masses (say, $m_{H^\pm}$), all the other tree-level Higgs masses are determined. It is important to note that $m_{H^\pm} \geq m_W$ and that one of the neutral Higgs, H^0_2, is always lighter than the Z. Hence, H^0_2 plays 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.

For simplicity, we shall take all $\tilde{q}_L$ and $\tilde{q}_R$ to be degenerate. When $M_{\tilde{g}} < M_{\tilde{q}}$ (our results are not sensitive to the precise $M_{\tilde{q}}$ choice; we take $M_{\tilde{q}} = 1.5M_{\tilde{g}}$), the dominant decays of the gluino are three-body tree-level decays: $\tilde{g} \to q\bar{q}'\tilde{\chi}^\pm_k$ and $\tilde{g} \to q\bar{q}\tilde{\chi}^0_k$. 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). However, over most of the supersymmetry model parameter space, such a specific assumption is incorrect and can lead to wrong conclusions. Our results are obtained by surveying supersymmetric parameter space and computing the neutralino/chargino masses and mixing angles obtained by diagonalizing the corresponding mass matrices. The only approximation that we make is to take the quarks which appear in the final state to be massless. Details and explicit formulas for the gluino decay widths can be found in ref. 1.

Of particular interest is the branching ratio of the gluino directly into the LSP (and associated $q\bar{q}$ pair). Such decays often lead to substantial missing energy. In fig. 1 we present gluino branching ratios to the LSP at $\tan\beta = 1.5$. (Branching ratios are invariant under $\tan\beta \to \cot\beta$.) Even for $M_{\tilde{g}} \sim 100\ GeV$ there is a very limited range of μ for which the direct $\tilde{g} \to LSP$ branching ratio is large. For larger $\tan\beta$ ($\gtrsim 4$), $BR(\tilde{g} \to LSP)$ is never larger than 40%; for $\tan\beta \approx 1$ the results resemble those for $\tan\beta = 1.5$. For $M_{\tilde{g}} \gtrsim 200$ no choices of the supersymmetric parameters lead to a branching ratio larger than 40%.

To see what decay modes of the $\tilde{g}$ are becoming important, we show in fig. 2 the branching ratios of a 1 TeV gluino into all possible chargino and neutralino final states, as a function of μ, with $\tan\beta = 1.5$. Over a large range of μ, the branching ratios for the various channels are flat (we call these regions the "plateaus"). Simple analytic expressions can be derived for the three plateau levels. The $\tilde{\chi}$'s with large branching ratios are those with large gaugino components.

Their associated masses at large $|\mu| > M$ are $M_{\tilde{\chi}^+_1} = M_{\tilde{\chi}^0_2} = M$ and $M_{\tilde{\chi}^0_1} = M'$, while at small $|\mu| < M$, large $M_{\tilde{g}}$ we have $M_{\tilde{\chi}^+_2} = M_{\tilde{\chi}^0_4} = M$ and $M_{\tilde{\chi}^0_3} = M'$. In each case, the remaining charginos and neutralinos are dominantly higgsino and have masses roughly equal to $|\mu|$. The branching ratios in the plateau regions are derived in ref. 1. As an example we quote the result

$$BR(\tilde{\chi}^0_3)||_{\mu|<M} = BR(\tilde{\chi}^0_1)||_{\mu|>M} = \frac{11x\tan^2\theta_W}{27 + 11x\tan^2\theta_W} \simeq 0.136,$$

where x varies from $x = 1.157$ to $x = 1.307$ as $M_{\tilde{q}}/M_{\tilde{g}}$ varies from 1 to ∞. The height of the $\tilde{\chi}^\pm_2$-$\tilde{\chi}^\pm_1$ plateau is $\simeq 0.58$, while that of $\tilde{\chi}^0_4$-$\tilde{\chi}^0_2$ is $\simeq 0.29$ (independent of $\tan\beta$). The large μ plateaus are present even for very small $M_{\tilde{g}}$. The small μ plateaus are evident only for $M_{\tilde{g}} \gtrsim 600\ GeV$.

The lesson of fig. 2 is that the dominant decay of the heavy gluino is typically into heavier chargino and neutralino states. These states will in turn decay into lighter charginos and neutralinos until the LSP is reached. The possible chains are numerous. Depending on the masses and mixing angles, one can emit W's, Z's, charged and neutral Higgs bosons, and quark and lepton pairs. We have made a systematic study of the possible resulting final states, and will present our full results in ref. 1.

When the gluino decays into a heavier neutralino or chargino, the resulting signature depends on the patterns of their subsequent decays. These were studied in detail in ref. 6. It was shown that the two-body decays of the neutralino and chargino $\tilde{\chi}_i \to \tilde{\chi}_j + X$ ($X = W, Z, H^\pm, H^0_{1,2,3}$) are dominant if kinematically allowed. One needs to specify one Higgs boson mass (in addition to μ, $M_{\tilde{g}}$ and $\tan\beta$) in order to uniquely determine the $\tilde{\chi}$ decay properties. There are four different categories of gluino decays: 1) Direct production of the LSP, $\tilde{g} \to q\bar{q}\tilde{\chi}^0_1$. 2) "Five-body" decay modes $\tilde{g} \to q\bar{q}f\bar{f}\tilde{\chi}_i$ ($f = q$ or l), where $f\bar{f}\tilde{\chi}_i$ originates directly from a three-body decay of a heavier chargino or neutralino. In this case, the intermediate $\tilde{\chi}$ possesses no two-body decay modes. 3)$\tilde{g} \to q\bar{q}\tilde{\chi}_i W$(or Z). 4)$\tilde{g} \to q\bar{q}\tilde{\chi}_i H$. In cases 3) and 4), the vector boson or Higgs boson originates from a two-body decay of a heavier $\tilde{\chi}$. In fig. 3, we present the branching ratios for gluinos into these four categories of decays. In this figure we take $\tan\beta = 1.5$ and $m_{H^+} = 150\ GeV$. For $\tan\beta \approx 1$ 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. However, if m_{H^+} is reduced to 90 GeV, there can be a substantial change for $M_{\tilde{g}} > 500\ GeV$. The branching fractions for the W and Z boson modes drop by as much as a factor of 2-3 for moderate negative values of μ, with the Higgs modes making up the difference. The impact is much smaller for positive μ and for $\mu < -M_{\tilde{g}}$.

In order to demonstrate the implications of the results presented in fig. 3, we assemble in Table 1 a list of possible signatures which could be used to identify gluino production. These are obtained by combining the $\tilde{g}\tilde{g}$ cross-sections with the gluino branching fractions. We compare results for the SSC to those for the LHC. The ranges of μ over which the various signals could be relevant are indicated. As an example, for an integrated luminosity of $10^4\ pb^{-1}$, we see from the Table that some very distinctive signals, such as $Z + LSP$ (with $Z \to l^+l^-$), would be very difficult to observe at the LHC but viable at the SSC.

It must be emphasized that Table 1 is intended to indicate signatures deserving further consideration. No attempt was made here to account for backgrounds, efficiencies or cuts. This must be left for future work. What is clear is that the search for gluinos at future supercolliders will be complex. Nevertheless, many interesting signatures are expected which, when taken together, could lead to clear evidence for supersymmetry.

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TABLE CAPTIONS

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

FIGURE CAPTIONS

1) The branching ratio for $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$ as a function of μ 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 $M_{\tilde{\chi}_1^+} < 30\ GeV$.

2) We give the branching ratios for $\tilde{g} \to q\bar{q}\tilde{\chi}_i^0$ and $\tilde{g} \to q\bar{q}'\tilde{\chi}_j^\pm$ ($i = 1,2,3,4$ and $j = 1,2$) as a function of μ for $M_{\tilde{g}} = 1\ TeV$ 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 $=\tilde{\chi}_4^0$.

3) 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 μ, taking $\tan\beta = 1.5$ and $m_{H^\pm} = 150\ GeV$.

Table 1

Approximate Event Rates for SSC vs. LHC

Signal	$M_{\tilde{g}} = 300\ GeV$	$M_{\tilde{g}} = 700\ GeV$	$M_{\tilde{g}} = 1000\ GeV$
1 direct LSP+any $\Rightarrow$jets+E_T^{miss}	**10^7 vs. 10^6** $(-\infty,-40);(160,\infty)$	**3×10^5 vs. 2×10^4** $(-\infty,-100);(70,\infty)$	**4×10^4 vs. 1700** $(-\infty,-140);(60,\infty)$
2 direct LSP $\Rightarrow$jets+E_T^{miss}	**10^6 vs. 10^5** $(-\infty,-40);(160,\infty)$	**20,000 vs. 1400** $(-\infty,-100);(70,\infty)$	**3000 vs. 130** $(-\infty,-140);(60,\infty)$
Two 5-body decays with leptons	**10^7 vs. 10^6** $(-\infty,30);(160,\infty)$	**6000 vs. 400** $(70,620)$	**240 vs. 10** $(200,300)$
Two Z's; $Z\to l^+l^-$	**1000 vs. 100** $(-40,30)$	**50 vs. 3** $(-200,0);(70,200)$	**10 vs. 0.4** $(-300,-10);(60,250)$
Z+ direct LSP; $Z\to l^+l^-$	**100 vs. 14** $(-40,30)$	**2000 vs. 130** $(-200,-100);(70,200)$	**300 vs. 13** $(-300,-140);(60,300)$
5-body+direct LSP; 5-body $\to$ leptons	**10^6 vs. 10^5** $(-\infty,-40);(160,\infty)$	**20,000 vs. 1400** $(-180,-100);(70,620)$	**1500 vs. 60** $(100,300)$
W+ direct LSP; $W\to$ leptons	**5×10^5 vs. 8×10^4** $(-100,-70)$	**20,000 vs. 1400** $(-\infty,-100);(70,250)$	**4000 vs. 170** $(-\infty,-140);(60,\infty)$
$W+Z$; $W,Z\to$ leptons	**3×10^4 vs. 4×10^3** $(-40,30)$	**1000 vs. 70** $(-200,0);(70,200)$	**200 vs. 8** $(-300,-140);(60,300)$

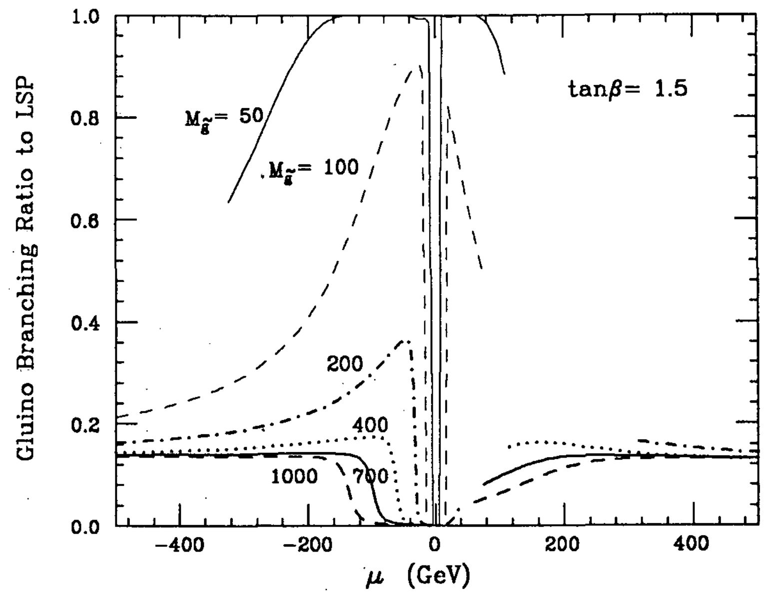


Figure 1

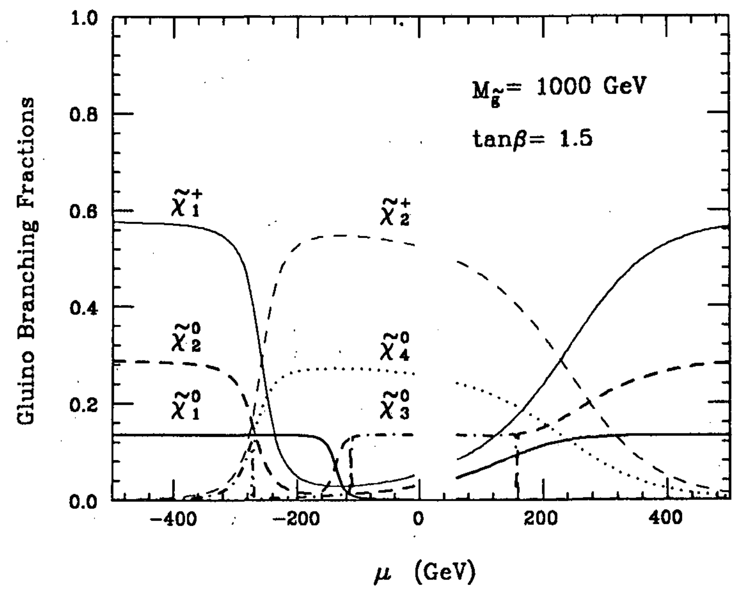
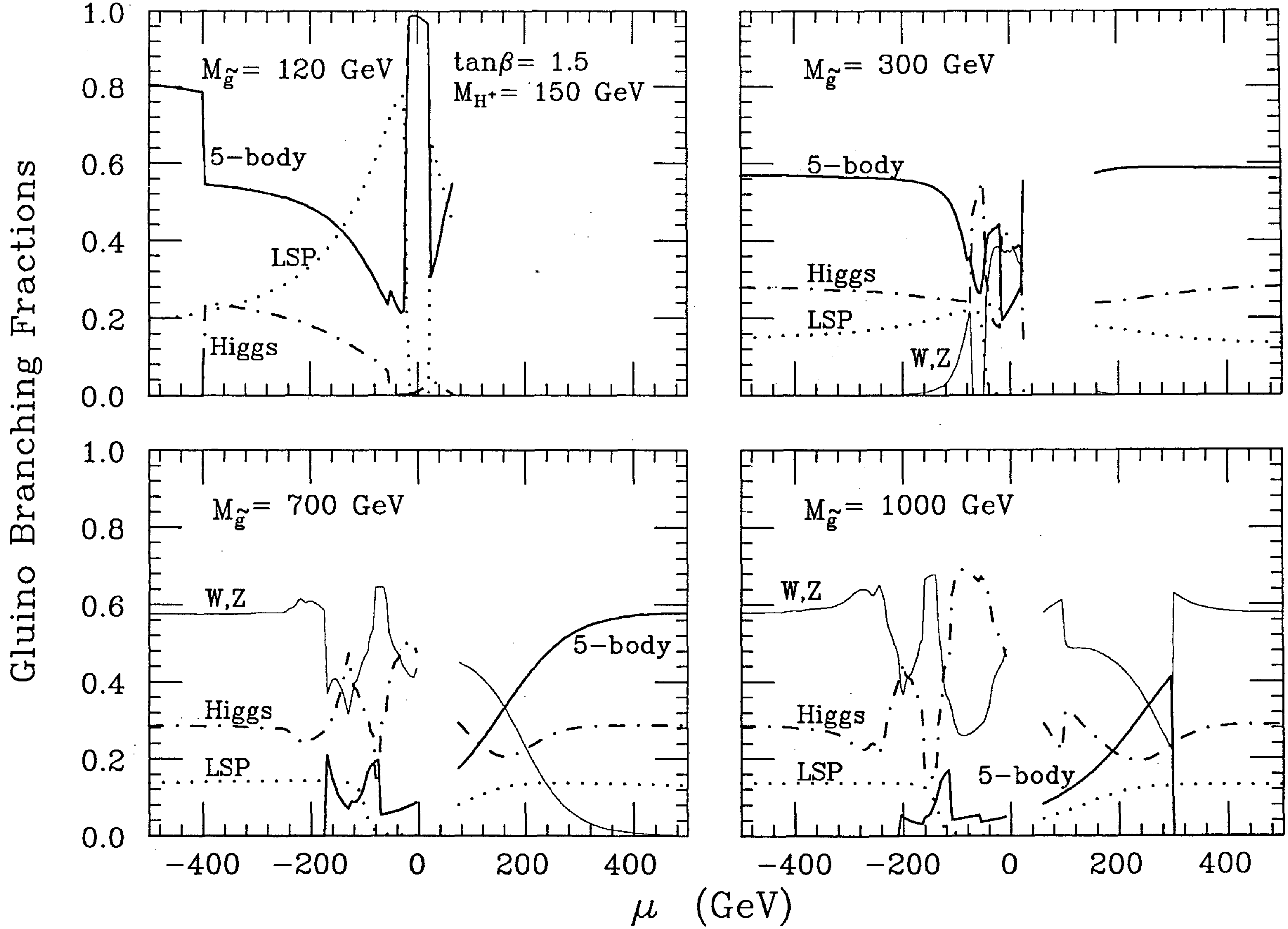


Figure 2



Gluino Branching Fractions
$M_{\tilde{g}}$= 120 GeV
tanβ= 1.5
M_{H^+}= 150 GeV
5−body
LSP
Higgs
$M_{\tilde{g}}$= 300 GeV
5−body
Higgs
LSP
W,Z
$M_{\tilde{g}}$= 700 GeV
W,Z
5−body
Higgs
LSP
$M_{\tilde{g}}$= 1000 GeV
W,Z
Higgs
LSP
5−body
μ (GeV)

Figure 3

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