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Detecting gluinos at hadron supercolliders

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If the gluino mass exceeds 150–200 GeV, searches for gluinos will likely have to be made at multi-TeV hadron colliders. Unlike the case of light gluinos ($m_{\tilde{g}} \lesssim 60$ GeV), which dominantly decay via $\tilde{g} \to q\bar{q}\tilde{\gamma}$, heavy-gluino decays proceed via $\tilde{g} \to q\bar{q}\tilde{W}_i$ and $\tilde{g} \to q\bar{q}\tilde{Z}_j$ where $\tilde{W}_i$ and $\tilde{Z}_j$ are charged and neutral mass eigenstates in the gauge-Higgs-fermion sector. The usual missing-p_T signatures are altered and new strategies may be required for gluino detection. We analyze heavy-gluino and scalar-quark decays and estimate the production rates for $\tilde{W}_i\tilde{W}_j$, $\tilde{W}_i\tilde{Z}_j$, and $\tilde{Z}_i\tilde{Z}_j$ pairs at a 40-TeV pp collider. Since a heavy gluino decays dominantly into jets and the heavy chargino, which in turn decays into a Z^0 or W boson plus a lighter chargino or neutralino, a typical gluino-pair event contains several leptons and/or jets in the final state.

I. INTRODUCTION

Supersymmetry (SUSY) provides an elegant solution to the gauge hierarchy problem of grand unified theories[1] provided the masses of the supersymmetric partners of the known particles do not exceed ~ 1 TeV. Since SUSY particles are produced in pairs, the limits on SUSY-particle masses from e^+e^- experiments[2] are typically equal to the beam energy $\lesssim 23$ GeV. There are also indirect mass limits from e^+e^- experiments such as that on the scalar-electron mass $m_{\tilde{e}} \gtrsim 66$ GeV (for $m_{\tilde{\gamma}} = 0$) obtained by the ASP experiment.[3] In a recent analysis of $\bar{p}p$ collider data the UA1 Collaboration concluded[4] that $m_{\tilde{q}} \gtrsim 70$ GeV and $m_{\tilde{g}} \gtrsim 60$ GeV provided that the photino is light and escapes detection.

With the forthcoming operation of the new machines, either SUSY particles will be found or these limits will be considerably improved. Limits on SUSY-particle masses of about $\frac{1}{2}M_Z$ should be attainable at the Stanford Linear Collider (SLC) and CERN LEP. Also, the Fermilab Tevatron should be sensitive to scalar-quark and gluino masses of up to about 150 GeV (Ref. 5). During the second phase of LEP, masses of 60–90 GeV for weakly interacting SUSY particles should be accessible.[6] If the SUSY-particle masses are larger than the values above, supersymmetry searches would have to be carried out at hadron supercolliders such as the proposed U.S. Superconducting Super Collider (SSC) or the European Hadron Facility (EHF).

At a hadron collider, strongly interacting particles have the largest production cross sections, and thus scalar quarks and gluinos are by far the most copiously produced SUSY particles.[7] In minimal $N=1$ supergravity models,[8] $m_{\tilde{g}} < 1.1\langle m_{\tilde{q}}{}^2\rangle^{1/2}$ [$\langle m_{\tilde{q}}{}^2\rangle$ is the average scalar-quark mass squared] so that the gluino mass is unlikely to be larger than the scalar-quark masses. Recent studies[9] of the SUSY-particle mass spectrum in the class of superstring models where supersymmetry breaking is induced by gaugino mass terms suggest that $m_{\tilde{g}} \approx \frac{1}{2}m_{\tilde{q}} \approx 0.3-1$ TeV. For these reasons, we primarily concentrate on the signals from the pair production of heavy gluinos at a multi-TeV hadron collider.

Signals from scalar-quark and gluino-pair production at the CERN collider have been extensively addressed in the literature.[5,10] It has been generally assumed that the scalar quarks and gluinos decay exclusively via $\tilde{q} \to q\tilde{g}$ or $\tilde{q} \to q\tilde{\gamma}$ and $\tilde{g} \to q\bar{q}\tilde{\gamma}$ or $\tilde{g} \to \tilde{q}q$ with the photino escaping detection. The classic signature for these events is then missing transverse momentum ($\not{p}_T$) from the escaping photino. If the gluinos and scalar quarks are substantially heavier, however, it is very likely that they would also decay into other neutralinos as well as into charginos with substantial branching fractions.[11,12] The neutralinos and charginos would further decay into the lightest supersymmetric particle (which is not necessarily the photino) plus hadrons or leptons. Because of the cascade decays involved, the missing transverse momentum from heavy gluinos is in general much less than it would be if the gluino decayed only to photinos. For gluino masses that can be searched for at the CERN S$p\bar{p}$S collider, the effect of these additional decay channels is not very significant[11] but for heavier gluinos and scalar quarks major changes in signals are likely. However, the cross sections for scalar-quark and gluino production are so large at supercollider energies that searches for these based on their direct decays to escaping neutralinos may still be feasible.

A general analysis of scalar-quark and gluino decays entails a discussion of mixings in the gauge-Higgs-fermion sector. For simplicity, our analysis is based on the minimal $N=1$ supergravity model. In the superstring-motivated models based on the grand unifying group E_6, there is a larger gauge-Higgs-fermion sector than in the minimal model. However, the additional charginos do not mix with those of our model and the mixing with the additional neutralinos is rather small (assuming that the additional gauge boson is heavy).[13] Our neglect of these extra fermions of E_6 is thus equivalent to the assumption that gluino decays into these additional fermions are suppressed.

Once the electroweak symmetry is broken the gauge and Higgs fermions mix to form the mass eigenstates.[1] The gauge-Higgs-fermion sector of the effective low-energy theory resulting from a minimal supergravity model can be parametrized in terms of three parameters, viz., (i) the supersymmetric Higgs-fermion mass term, $2m_1$, (ii) soft-SUSY-breaking gaugino masses determined by the gluino mass $m_{\tilde g}$, and (iii) the ratio v'/v of the vacuum expectation values of the Higgs fields h and h' that give masses to the $T_{3L}=+\frac{1}{2}$ and $T_{3L}=-\frac{1}{2}$ fermions, respectively. We obtain exact mass eigenstates in both the charged and neutral sectors allowing for variations of these three parameters. For large gluino masses, the usual simplification of neglecting the SUSY-breaking gaugino mass in discussing the neutralino mixings is invalid. This complicates the neutralino sector which then has to be diagonalized numerically. All the chargino and neutralino masses and couplings are thus given in terms of these three parameters. A SUSY-breaking scalar-fermion mass (or, alternatively, the scalar-quark mass) suffices to fix the scalar-quark and scalar-lepton masses.

The heavy gluino decays mainly via the chargino mode, with the decay $\tilde g \to q\bar q \tilde W_+$ to the heavier chargino $\tilde W_+$ dominating for most values of the parameters. The subsequent decays of $\tilde W_+$ are complicated but for a large region of parameters it decays via $\tilde W_+ \to W + \tilde Z_i$ to one of the lighter neutralinos $\tilde Z_i$ or via $\tilde W_+ \to Z^0 + \tilde W_-$ to the lighter chargino $\tilde W_-$. A characteristic feature of a heavy-gluino pair event would be the presence of W and/or Z bosons in the final state in a substantial fraction of the events. The W and/or Z bosons, the $\tilde W_-$ and possibly also the $\tilde Z_i$ would further decay either leptonically or hadronically giving rise to final states with several jets, several leptons, and $\not p_T$.

The pair production of gluinos and scalar quarks is expected to be the most copious source of gaugino pairs at a hadron supercollider. The cross section is strongly dependent on $m_{\tilde g}$ ($m_{\tilde q}$) varying from ~ 10 nb for $m_{\tilde g} \simeq 250$ GeV to ~ 100 pb for $m_{\tilde g}=750$ GeV. Assuming an annual integrated luminosity of 10^4 pb^{-1} at the SSC these cross sections correspond to $\gtrsim 10^6$ gaugino pairs. Such large rates would permit a trigger on the rarer but cleaner leptonic decays of some of the gauginos and gauge bosons.

The remainder of this paper is organized as follows. In Sec. II we briefly discuss the model and obtain the mass eigenstates and the couplings in the gauge-Higgs-fermion sector of the theory. The decays of heavy gluinos and scalar quarks are discussed in Sec. III. Section IV is devoted to a study of event rates and signatures for gluino-pair events at the SSC. Our conclusions and some general remarks are presented in Sec. V.

II. THE SUPERSYMMETRIC MODEL

In this section, we introduce our model for the couplings of the mass eigenstates in the gauge-Higgs-fermion sector of the low-energy theory obtained by integrating out the heavy degrees of freedom present in the fundamental theory. In addition to the SU(2) and U(1) gauge fermions λ and λ_0, all SUSY models contain at least two Higgs doublets h and h' whose vacuum expectation values give masses to the $T_{3L}=\frac{1}{2}$ and $T_{3L}=-\frac{1}{2}$ fermions. The mass terms in the charged sector take the form

$$(\bar\lambda,\bar\chi)(M_{(\text{charge})}P_L + M^T_{(\text{charge})}P_R)\begin{bmatrix}\lambda\\ \chi\end{bmatrix} . \tag{2.1}$$

The Dirac spinors λ and χ are defined by

$$\lambda \equiv 1/\sqrt{2}(\lambda_1 + i\lambda_2),\quad \chi \equiv P_L h' - P_R h ,$$

with P_L (P_R) being the chirality projector for left- (right-) handed states. In the neutralino sector the mass terms are

$$\tfrac{1}{2}(\bar h^0, \bar h'^0, \bar\lambda_3, \bar\lambda_0)(M_{(\text{neutral})}P_L + M_{(\text{neutral})}P_R)\begin{bmatrix}h^0\\ h'^0\\ \lambda_3\\ \lambda_0\end{bmatrix} . \tag{2.2}$$

The mass matrices are given by[1]

$$M_{(\text{charge})} = \begin{bmatrix}\mu_2 & gv'\\ gv & 2m_1\end{bmatrix} \tag{2.3}$$

and

$$M_{(\text{neutral})} = \begin{bmatrix} 0 & -2m_1 & \frac{1}{\sqrt{2}}gv & \frac{-1}{\sqrt{2}}g'v \\ -2m_1 & 0 & \frac{-1}{\sqrt{2}}gv' & \frac{1}{\sqrt{2}}g'v' \\ \frac{1}{\sqrt{2}}gv & \frac{-1}{\sqrt{2}}gv' & \mu_2 & 0 \\ \frac{-1}{\sqrt{2}}g'v & \frac{1}{\sqrt{2}}g'v' & 0 & \mu_1 \end{bmatrix} , \tag{2.4}$$

where v, v', and m_1 were defined in Sec. I, μ_2 and μ_1 are the SU(2) and U(1) gaugino masses, and g and g' are the SU(2) and U(1) gauge couplings. We assume that there is a grand unification with canonical kinetic terms for the gauge fields. The gaugino masses generated by radiative corrections then satisfy

$$\frac{\mu_1}{\alpha_1}=\frac{\mu_2}{\alpha_2}=\frac{\mu_3}{\alpha_3} . \tag{2.5}$$

Here μ_3 is the SU(3) gaugino mass and the α_i with $i=3,2,1$ are the SU(3), SU(2), and U(1) fine-structure constants. The gluino mass $m_{\tilde{g}}$ is $|\mu_3|$; since the gauge couplings and v are known, the mass matrices are determined in terms of just two other parameters, v'/v and $2m_1$. Our inputs α_i at the scalar M_W are fixed by $\alpha_{\text{EM}}=\frac{1}{128}$, $\sin^2\theta_W=0.22$, and $\alpha_3=0.136$.

The diagonalization of these mass matrices has been discussed by a number of authors.[14] The discussion presented here is for the sake of completeness and for the purpose of setting up the notation. The charged sector can be diagonalized by rotating the left- and right-handed components of the fields by different angles γ_L and γ_R ($0\le\gamma_L,\gamma_R\le 180°$) given by

$$\tan\gamma_L=1/x_-,\quad \tan\gamma_R=1/y_- , \tag{2.6}$$

where

$$\begin{aligned} x_-&=\frac{(4m_1{}^2-\mu_2{}^2-2M_W{}^2\cos2\alpha)-\zeta}{2\sqrt{2}M_W(\mu_2\sin\alpha+2m_1\cos\alpha)} ,\\ y_-&=\frac{(4m_1{}^2-\mu_2{}^2+2M_W{}^2\cos2\alpha)-\zeta}{2\sqrt{2}M_W(\mu_2\cos\alpha+2m_1\sin\alpha)} , \end{aligned} \tag{2.7}$$

with

$$\begin{aligned} &\tan\alpha=v'/v ,\\ &\zeta^2=(4m_1{}^2-\mu_2{}^2)^2+4M_W{}^2(M_W{}^2\cos^22\alpha+4m_1{}^2+\mu_2{}^2\\ &\qquad\qquad +4m_1\mu_2\sin2\alpha) . \end{aligned} \tag{2.8}$$

The masses m_- and m_+ of the eigenstates $\tilde{W}_-$ and $\tilde{W}_+$ are given by

$$\begin{aligned} m_+&=\theta_x\theta_y[\cos\gamma_R(\mu_2\cos\gamma_L-gv'\sin\gamma_L)\\ &\qquad -\sin\gamma_R(gv\cos\gamma_L-2m_1\sin\gamma_L)] ,\\ m_-&=\sin\gamma_R(\mu_2\sin\gamma_L+gv'\cos\gamma_L)\\ &\qquad +\cos\gamma_R(gv\sin\gamma_L+2m_1\cos\gamma_L) . \end{aligned} \tag{2.9}$$

Here $\theta_x=\text{sgn}(x_-)$ and $\theta_y=\text{sgn}(y_-)$. The squares of these masses can also be obtained as the eigenvalues of the matrix $M_{(\text{charge})}M^T_{(\text{charge})}$ defined in Eq. (2.3); from this we find

$$m_\pm{}^2=\tfrac{1}{2}(4m_1{}^2+2M_W{}^2+\mu_2{}^2\pm\zeta) .$$

The masses given by Eq. (2.9) may be negative in which case we use the spinor $\gamma_5\tilde{W}$ rather than $\tilde{W}$ as the field with positive mass when computing the couplings.

The mass eigenstates for the left- and right-handed components of the charginos are

$$\begin{bmatrix}\tilde{W}_+\\ \tilde{W}_-\end{bmatrix}_L=\begin{bmatrix}\theta_x\cos\gamma_L & -\theta_x\sin\gamma_L\\ \sin\gamma_L & \cos\gamma_L\end{bmatrix}\begin{bmatrix}\lambda\\ \chi\end{bmatrix}_L \tag{2.10}$$

and

$$\begin{bmatrix}(-1)^{\theta_+}\tilde{W}_+\\ (-1)^{\theta_-}\tilde{W}_-\end{bmatrix}_R=\begin{bmatrix}\theta_y\cos\gamma_R & -\theta_y\sin\gamma_R\\ \sin\gamma_R & \cos\gamma_R\end{bmatrix}\begin{bmatrix}\lambda\\ \chi\end{bmatrix}_R , \tag{2.11}$$

where

$$\theta_\pm=\begin{cases}0 & \text{if } m_\pm>0 ,\\ 1 & \text{if } m_\pm<0 .\end{cases}$$

Next, we turn to the diagonalization of the neutralino mass matrix (2.4). The matrix is difficult to diagonalize analytically. We obtained all the eigenvectors and eigenvalues numerically for input values of $2m_1$, v'/v, and μ_i. The current eigenstates can be written in terms of the mass eigenstates $\tilde{Z}_i$ as

$$\begin{bmatrix}h^0\\ h'^0\\ \lambda_3\\ \lambda_0\end{bmatrix}=\begin{bmatrix}v_1^{(1)} & v_1^{(2)} & v_1^{(3)} & v_1^{(4)}\\ v_2^{(1)} & v_2^{(2)} & v_2^{(3)} & v_2^{(4)}\\ v_3^{(1)} & v_3^{(2)} & v_3^{(3)} & v_3^{(4)}\\ v_3^{(1)} & v_4^{(2)} & v_4^{(3)} & v_4^{(4)}\end{bmatrix}\begin{bmatrix}(-i\gamma_5)^{\theta_1}\tilde{Z}_1\\ (-i\gamma_5)^{\theta_2}\tilde{Z}_2\\ (-i\gamma_5)^{\theta_3}\tilde{Z}_3\\ (-i\gamma_5)^{\theta_4}\tilde{Z}_4\end{bmatrix} , \tag{2.12}$$

where θ_i equals 0 (1) if the mass of $\tilde{Z}_i$ is positive (negative). The factor $(-i\gamma_5)^{\theta_i}$ in Eq. (2.12) is to ensure that we are dealing with positive mass fields that are self-conjugate. The coefficients $v_i^{(j)}$ are numerically calculated. The couplings of the fields h, h', λ, and λ^0 are all fixed by SU(2)$\times$U(1) and supersymmetry and those for the mass eigenstates can now be readily obtained. We find

$$\begin{aligned} \mathcal{L}_{q\tilde{q}\tilde{g}}&=\sqrt{2}ig_s\tilde{q}^{\dagger}_L\bar{\tilde{g}}_A\frac{\lambda_A}{2}\frac{1-\gamma_5}{2}q\\ &\quad+\sqrt{2}ig_s\tilde{q}^{\dagger}_R\bar{\tilde{g}}_A\frac{\lambda_A}{2}\frac{1+\gamma_5}{2}q+\text{H.c.} ,\\ \mathcal{L}_{q\tilde{q}\tilde{Z}_i}&=iA^q_{\tilde{Z}_i}\tilde{q}^{\dagger}_L\bar{\tilde{Z}}_i\frac{1-\gamma_5}{2}q+iB^q_{\tilde{Z}_i}\tilde{q}^{\dagger}_R\bar{\tilde{Z}}_i\frac{1+\gamma_5}{2}q+\text{H.c.} ,\\ \mathcal{L}_{q\tilde{q}\tilde{W}_\pm}&=iA^d_{\tilde{W}_i}\tilde{u}^{\dagger}_L\bar{\tilde{W}}_i\frac{1-\gamma_5}{2}d+iA^u_{\tilde{W}_i}\tilde{d}^{\dagger}_L\bar{\tilde{W}}{}^c_i\frac{1-\gamma_5}{2}u , \end{aligned} \tag{2.13}$$

$$\begin{aligned} \mathcal{L}_{W\tilde{W}_i\tilde{Z}_j}&=-g(-i)^{\theta_j}\sum_{i=\pm}\bar{\tilde{W}}_i(X^j_{(i)}+Y^j_{(i)}\gamma_5)\gamma^\mu\tilde{Z}_jW_\mu+\text{H.c.} ,\\ \mathcal{L}_{Z\tilde{W}_+\tilde{W}_-}&=(-1)^{\theta_++\theta_-}\frac{e}{2}(\cot\theta_W+\tan\theta_W)\\ &\quad\times\bar{\tilde{W}}_-\gamma^\mu(x\gamma_5-y)(\gamma_5)^{\theta_++\theta_-}\tilde{W}_+Z_\mu+\text{H.c.} \end{aligned}$$

In the last equation above x and y are defined as

$$\begin{aligned} x&=\tfrac{1}{2}(\theta_x\sin\gamma_L\cos\gamma_L-\theta_y\sin\gamma_R\cos\gamma_R) ,\\ y&=\tfrac{1}{2}(\theta_x\sin\gamma_L\cos\gamma_L+\theta_y\sin\gamma_R\cos\gamma_R) . \end{aligned} \tag{2.14}$$

The coefficients $A_{\tilde{Z}_i}$, $B_{\tilde{Z}_i}$, and $A^q_{\tilde{W}_i}$ that appear in Eq. (2.13) are given by

$$
\begin{aligned}
A^u_{\tilde{Z}_i} &= (i)^{\theta_i - 1}(-1)^{\theta_i+1}\left[\frac{g}{\sqrt{2}}v_3^{(i)} + \frac{g'}{3\sqrt{2}}v_4^{(i)}\right],\\
A^d_{\tilde{Z}_i} &= (i)^{\theta_i - 1}(-1)^{\theta_i+1}\left[\frac{-g}{\sqrt{2}}v_3^{(i)} + \frac{g'}{3\sqrt{2}}v_4^{(i)}\right],\\
B^u_{\tilde{Z}_i} &= \tfrac{4}{3}(i)^{\theta_i - 1}\frac{g'}{\sqrt{2}}v_4^{(i)},\\
B^d_{\tilde{Z}_i} &= -\tfrac{2}{3}(i)^{\theta_i - 1}\frac{g'}{\sqrt{2}}v_4^{(i)},\\
A^d_{\tilde{W}_-} &= ig(-1)^{\theta_-}\sin\gamma_R, \quad A^d_{\tilde{W}_+} = ig(-1)^{\theta_+}\theta_y\cos\gamma_R,\\
A^u_{\tilde{W}_-} &= ig\sin\gamma_L, \quad A^u_{\tilde{W}_+} = ig\theta_x\cos\gamma_L .
\end{aligned}
\tag{2.15}
$$

Finally, the $X^j_{(i)}$ that appear in Eq. (2.13) are given by

$$
\begin{aligned}
X^j_{(-)} &= \frac{1}{2}\left[(-1)^{\theta_- + \theta_j}\left[\frac{\cos\gamma_R}{\sqrt{2}}v_1^{(j)} + \sin\gamma_R v_3^{(j)}\right] - \frac{\cos\gamma_L}{\sqrt{2}}v_2^{(j)} + \sin\gamma_L v_3^{(j)}\right],\\
X^j_{(+)} &= \frac{1}{2}\left[(-1)^{\theta_+ + \theta_j}\theta_y\left[\frac{-\sin\gamma_R}{\sqrt{2}}v_1^{(j)} + \cos\gamma_R v_3^{(j)}\right] + \theta_x\left[\frac{\sin\gamma_L}{\sqrt{2}}v_2^{(j)} + \cos\gamma_L v_3^{(j)}\right]\right],
\end{aligned}
\tag{2.16}
$$

and the $Y^j_{(\pm)}$ can be obtained from $X^j_{(\pm)}$ by changing the sign of just the first term inside the square brackets.

Using the couplings in Eq. (2.13), we can now calculate the decays of the gluinos and scalar quarks that may be relevant at supercollider energies. Before proceeding to do so, we briefly discuss the eigenvalues and eigenvectors for the charginos and neutralinos that result from the diagonalization. The gaugino masses μ_i are given in terms of $m_{\tilde{g}}$. We take all $\mu_i<0$ so that $\mu_3=-m_{\tilde{g}}$; μ_1 and μ_2 are then determined from Eq. (2.5). We list the eigenvalues and eigenvectors for the four neutralino and the two chargino states in Table I for representative values of $2m_1$ and v'/v, for the cases $v'/v=1.0$ and 0.4. The former is the value favored by supergravity models in which $SU(2)\times U(1)$ is radiatively[15] broken by a top quark with a mass ~ 40 GeV whereas the latter is seemingly favored[9] in some superstring-motivated models. We have varied the Higgs-fermion mass term around its typical value $O(M_W)$ considering both signs for it. We have checked that our results for the $\tilde{W}_-$, $\tilde{Z}_1$ and $\tilde{Z}_2$ masses agree with those of Ellis *et al.*[14] The following features are worth noting.

(i) For $v'/v=1$, $(1/2)(h^0+h'^0)$ is always an eigenstate with eigenvalue $-2m_1$ (a Higgs fermion).

(ii) For smaller values of gaugino masses (i.e., small $m_{\tilde{g}}$), the photino ($\tilde{\gamma}\equiv\sin\theta_W\lambda_3+\cos\theta_W\lambda_0$) is an approximate eigenstate but in general this is not the case. In fact, for large gaugino masses, λ_3 and λ_0 are approximate mass eigenstates. Most generally, the neutralinos are complex mixtures of all four states and it is not possible to think in terms of photino, Z-gaugino, and Higgs-fermion states.

(iii) The masses and eigenvectors (and hence the couplings) are sensitive to the sign of the Higgs-fermion mass term.

(iv) For small gluino masses, the lightest neutralino is largely a gaugino (unless $2m_1\approx 0$) whereas the opposite is true for large gluino masses (unless $2m_1$ is very large).

(v) For $v'/v=1$, the left- and right-hand chargino eigenvectors are the same except for an overall sign if the chargino mass is negative. This follows from Eq. (2.11) and the fact $x_-=y_-$ if $v'/v=1$. In general though, the couplings of the left- and right-handed charginos are quite different.

(vi) The masses of the neutralinos and charginos vary over a wide range depending on the parameters. A few of these parameters are already disallowed by present data, e.g., the $2m_1=-M_W$ case for $m_{\tilde{g}}=500$ GeV leads to a light chargino with a mass of 20.5 GeV which is ruled out by the DESY PETRA data.[2,16]

(vii) For $v'/v=r>1$, the eigenvalues are the same as those for $v'/v=1/r$. However the eigenvectors change; the left- and right-handed components of the chargino interchange with the corresponding case for $v'/v=1/r$. In the neutralino case, the h and h' components interchange in magnitude whereas the magnitudes of the λ_3 and λ_0 components, and hence the gaugino content of the neutralino, is unaltered.

This completes our discussion of the mixings and mass eigenstates in the gauge-Higgs-fermion sector. We now turn to the analysis of scalar-quark and gluino decays that would be relevant for a discussion of their signals at a hadron collider.

III. THE DECAYS OF HEAVY SCALAR QUARKS AND GLUINOS

In many models gluinos are expected to be lighter than the scalar quark so that the decay $\tilde{g}\to q\bar{\tilde{q}}$ or $\bar{q}\tilde{q}$ to real scalar quarks is kinematically inaccessible. Also, at least one of the neutralinos is lighter than the gluino so that it can decay via a three-body mode $\tilde{g}\to q\bar{q}\tilde{Z}_1$. In previous analyses,[10] it has usually been assumed that $\tilde{Z}_1=\tilde{\gamma}$. For a heavy gluino, additional decay channels into other neutralinos and also into charginos may be possible[11,12] so that the gluino signals at a hadron collider become considerably more complicated.

If the scalar quark is considerably heavier than the gluino, the strong decay $\tilde{q}\to q\tilde{g}$ dominates over the electroweak decays $\tilde{q}\to q\tilde{W}_i$, $\tilde{q}\to q\tilde{Z}_i$. The right-handed scalar quark cannot decay into charginos and its branching fraction into the gluino mode is around 98% whereas that for the left-handed scalar quark varies between 80% and 90% since it also has a chargino decay channel.

Gluino decays into neutralinos take place via virtual scalar quarks of both handedness whereas the decays to charginos take place only via left-handed scalar quarks. For massless quarks in the final state, the left- and right-handed scalar-quark exchanges do not interfere and the color- and spin-averaged-squared matrix elements are

TABLE I. Eigenvalues (in GeV) and eigenvectors for neutralinos in the basis $(h^0,h'^0,\lambda_3,\lambda_0)$ and charginos in the basis (λ,χ) for $m_{\tilde{g}}$ equal to (a) 150 GeV, (b) 500 GeV, and (c) 1000 GeV. The first vector in the chargino case is that for the left-handed state while the second one is for the right-handed state. For $v'/v=1$, the two eigenvectors are the same except for a sign when the eigenvalue is negative. This reflects the fact that the mass matrix (2.1) becomes γ_5 independent when $v'/v=1$, and so does not require a biunitary transformation for its diagonalization. In the neutralino sector the $\tilde{\gamma}$ is the eigenvector $(0,0,\sin\theta_W,\cos\theta_W)$. The behavior of the eigenvectors for $v'/v>1$ is discussed in the text.

ϵ	v'/v		Neutralinos $(h^0,h'^0,\lambda_3,\lambda_0)$		Charginos (λ,χ)
			(a) $m_{\tilde{g}}=150$ GeV		
M_W	1	-22.2	$(0.05,-0.05,0.39,0.92)$	-81.1	$(0.89,-0.45)$
		-83.0	$(0.71,0.71,0,0)$		$(-0.89,0.45)$
		-87.5	$(-0.34,0.34,0.82,-0.31)$	125.0	$(0.45,0.89)$
		135.2	$(-0.62,0.62,-0.42,0.25)$		$(0.45,0.89)$
M_W	0.4	-21.8	$(-0.02,0.14,-0.34,-0.93)$	-58.4	$(0.59,-0.81)$
		-50.7	$(0.21,0.75,0.61,-0.12)$		$(-1.0,-0.04)$
		-115.4	$(0.71,0.32,-0.59,0.24)$	-137.1	$(0.81,0.59)$
		130.2	$(0.68,-0.56,0.41,-0.25)$		$(-0.04,1.0)$
$0.1M_W$	1	-8.3	$(0.71,0.71,0,0)$	70.9	$(0.60,0.80)$
		-22.7	$(0.06,-0.06,0.44,0.89)$		$(0.60,0.80)$
		83.5	$(-0.55,0.55,-0.53,0.34)$	-101.8	$(0.80,-0.60)$
		-110.1	$(0.44,-0.44,-0.73,0.30)$		$(-0.80,0.60)$
$-M_W$	1	-23.5	$(0.07,-0.07,0.52,0.85)$	24.8	$(0.79,0.61)$
		39.0	$(-0.43,0.43,-0.64,0.47)$		$(0.79,0.61)$
		83.0	$(0.71,0.71,0,0)$	-146.9	$(0.61,-0.79)$
		-156.1	$(0.56,-0.56,-0.56,0.25)$		$(-0.61,0.79)$
$4M_W$	1	-21.1	$(-0.04,0.04,-0.27,-0.96)$	-56.9	$(0.98,-0.21)$
		-59.2	$(-0.16,0.16,0.94,-0.25)$		$(-0.98,0.21)$
		-332.0	$(0.71,0.71,0,0)$	349.7	$(0.21,0.98)$
		354.7	$(0.69,-0.69,0.20,-0.11)$		$(0.21,0.98)$
			(b) $m_{\tilde{g}}=500$ GeV		
M_W	1	-68.8	$(0.11,-0.11,0.22,0.96)$	111.5	$(0.32,0.95)$
		-83.0	$(0.71,0.71,0,0)$		$(0.32,0.95)$
		121.0	$(0.65,-0.65,0.31,-0.22)$	-159.1	$(0.95,-0.32)$
		-161.3	$(0.24,-0.24,-0.93,0.15)$		$(-0.95,0.32)$
M_W	0.4	-59.8	$(0.27,0.60,0.03,-0.76)$	-90.8	$(0.16,-0.99)$
		-79.4	$(0.47,0.52,0.39,0.59)$		$(-0.70,-0.71)$
		116.8	$(0.70,-0.61,0.30,-0.22)$	-171.7	$(0.99,0.16)$
		-169.6	$(-0.46,-0.05,0.87,-0.17)$		$(-0.71,0.70)$
$0.1M_W$	1	-8.3	$(0.71,0.71,0,0)$	47.1	$(0.42,0.91)$
		60.3	$(+0.62,-0.62,0.38,-0.32)$		$(0.42,0.91)$
		-71.3	$(0.15,-0.15,0.29,0.93)$	-169.4	$(0.91,-0.42)$
		-172.7	$(0.31,-0.31,-0.88,0.18)$		$(-0.91,0.42)$
$-M_W$	1	0.73	$(0.51,-0.51,0.46,-0.51)$	-20.5	$(0.60,0.80)$
		-77.0	$(-0.21,0.21,-0.46,-0.83)$		$(-0.60,-0.80)$
		83.0	$(0.71,0.71,0,0)$	-193.1	$(0.80,-0.60)$
		-198.6	$(0.44,-0.44,-0.76,0.20)$		$(-0.80,0.60)$
$4M_W$	1	-65.0	$(0.06,-0.06,0.11,0.99)$	-145.0	$(0.99,-0.17)$
		-145.8	$(-0.13,0.13,0.98,-0.09)$		$(-0.99,0.17)$
		-332.0	$(0.71,0.71,0,0)$	346.4	$(0.17,0.99)$
		351.0	$(-0.69,0.69,-0.17,0.10)$		$(0.17,0.99)$
			(c) $m_{\tilde{g}}=1000$ GeV		
M_W	1	-83.0	$(0.71,0.71,0,0)$	102.0	$(0.22,0.97)$
		109.9	$(0.68,-0.68,0.21,-0.18)$		$(0.22,0.97)$
		-130.1	$(-0.12,0.12,-0.10,-0.98)$	-280.2	$(0.97,-0.22)$
		-280.8	$(-0.16,0.16,0.97,-0.06)$		$(-0.97,0.22)$
M_W	0.4	-74.5	$(0.59,0.76,0.12,-0.24)$	93.3	$(0.03,1.0)$
		106.5	$(-0.72,0.64,-0.20,0.17)$		$(0.38,0.93)$
		-132.7	$(0.26,0.08,0.14,0.95)$	-283.2	$(1.0,-0.03)$
		-283.3	$(0.26,0.03,-0.96,0.07)$		$(-0.93,0.38)$

TABLE I. (*Continued*).

ϵ	v'/v	Neutralinos	$(h^0,h'^0,\lambda_3,\lambda_0)$	Charginos	(λ,χ)
$0.1M_W$	1	-8.3	$(0.71,0.71,0,0)$	31.8	$(0.27,0.96)$
		42.7	$(-0.66,0.66,-0.26,0.25)$		$(0.27,0.96)$
		-132.8	$(0.15,-0.15,0.14,0.97)$	-284.7	$(0.96,-0.27)$
		-285.6	$(-0.20,0.20,0.96,-0.08)$		$(-0.96,0.27)$
$-M_W$	1	-31.7	$(-0.61,0.61,-0.31,0.41)$	-50.3	$(0.37,0.93)$
		83.0	$(0.71,0.71,0,0)$		$(-0.37,-0.93)$
		-139.9	$(0.25,-0.25,0.24,0.91)$	-293.9	$(0.93,-0.37)$
		-295.4	$(-0.27,0.27,0.92,-0.10)$		$(-0.93,0.37)$
$4M_W$	1	-126.6	$(0.06,-0.06,0.05,0.99)$	-272.6	$(0.99,-0.14)$
		-272.8	$(-0.10,0.10,0.99.-0.04)$		$(-0.99,0.14)$
		-332.0	$(0.71,0.71,0,0)$	343.4	$(0.14,0.99)$
		347.5	$(-0.70,0.70,-0.13,0.09)$		$(0.14,0.99)$

$$
\begin{aligned}
&|\mathcal{M}_L(\tilde{g}\to q\bar{q}\tilde{Z}_i)|^2=2g_s^2\,|A^q_{\tilde{Z}_i}|^2[\psi(m_{\tilde{g}},m_{\tilde{q}_L},m_{\tilde{Z}_i})+(-1)^{\theta_i-1}\phi(m_{\tilde{g}},m_{\tilde{q}_L},m_{\tilde{Z}_i})]\;,\\
&|\mathcal{M}_R(\tilde{g}\to q\bar{q}\tilde{Z}_i)|^2=2g_s^2\,|B^q_{\tilde{Z}_i}|^2[\psi(m_{\tilde{g}},m_{\tilde{q}_R},m_{\tilde{Z}_i})+(-1)^{\theta_i-1}\phi(m_{\tilde{g}},m_{\tilde{q},R},m_{\tilde{Z}_i})]\;,\\
&|\mathcal{M}_L(\tilde{g}\to q\bar{q}'\tilde{W}_i)|^2=2g_s^2[\tfrac{1}{2}(|A^d_{\tilde{W}_i}|^2+|A^u_{\tilde{W}_i}|^2)\psi(m_{\tilde{g}},m_{\tilde{q}_L},m_{\tilde{W}_i})+\mathrm{Re}(A^u_{\tilde{W}_i}A^d_{\tilde{W}_i})\phi(m_{\tilde{g}},m_{\tilde{q}_L},m_{\tilde{W}_i})]\;,\\
&|\mathcal{M}_R(\tilde{g}\to q\bar{q}\tilde{W}_i)|^2=0\;,
\end{aligned}
\tag{3.1}
$$

where

$$
\begin{aligned}
\psi(m_{\tilde{g}},m_{\tilde{q}},m)&=\pi^2 m_{\tilde{g}}\int dq\frac{q^2(m_{\tilde{g}}{}^2-2m_{\tilde{g}}q-m^2)^2}{(m_{\tilde{g}}{}^2-2m_{\tilde{g}}q-m_{\tilde{q}}{}^2)^2(m_{\tilde{g}}{}^2-2m_{\tilde{g}}q)}\;,\\
\phi(m_{\tilde{g}},m_{\tilde{q}},m)&=\tfrac{1}{2}\pi^2 m_{\tilde{g}}m\int\frac{dq}{m_{\tilde{g}}{}^2-m_{\tilde{q}}{}^2-2m_{\tilde{g}}q}\left[\frac{-q(m_{\tilde{g}}{}^2-m^2-2m_{\tilde{g}}q)}{m_{\tilde{g}}(m_{\tilde{g}}-2q)}\right.\\
&\qquad\left.-\frac{2m_{\tilde{g}}q-m_{\tilde{q}}{}^2+m^2}{2m_{\tilde{g}}}\ln\frac{m_{\tilde{q}}{}^2(m_{\tilde{g}}-2q)-m_{\tilde{g}}m^2}{(m_{\tilde{g}}-2q)(m_{\tilde{q}}{}^2-2m_{\tilde{g}}q-m^2)}\right]\;.
\end{aligned}
\tag{3.2}
$$

The range of integration in Eqs. (3.2) is from 0 to $(m_{\tilde{g}}{}^2-m^2)/2m_{\tilde{g}}$. The partial widths are

$$\Gamma=\frac{1}{2m_{\tilde{g}}}\frac{1}{(2\pi)^5}(|\mathcal{M}_L|^2+|\mathcal{M}_R|^2)\;. \tag{3.3}$$

The branching fractions for gluino decays are shown in Figs. 1 and 2. In Fig. 1 the Higgs-fermion mixing mass is fixed at M_W and v'/v values of 1 and 0.4 are considered. In Fig. 2 the Higgs-fermion mass is varied with $v'/v=1$. The branching fractions exhibit a rather complex behavior, which is discussed below. In the following, the neutralinos $\tilde{Z}_1$, $\tilde{Z}_2$, $\tilde{Z}_3$, $\tilde{Z}_4$ are labeled in order of increasing masses.

(i) For small values of $m_{\tilde{g}}$, the gluino decays exclusively via $\tilde{g}\to q\bar{q}\tilde{Z}_1$ with the exception of Fig. 2(a), where $\tilde{Z}_1$ is the Higgs fermion, and the decay $\tilde{g}\to q\bar{q}\tilde{Z}_1$ does not take place via the tree graph. (It will, however, take place via a one-loop graph, where the Higgs fermion couples to the gauge boson and gaugino.)

(ii) As soon as the decay $\tilde{g}\to q\bar{q}'\tilde{W}_-$ becomes kinematically accessible, it becomes a significant fraction of the gluino decay.

(iii) The curves all exhibit "breaks" marked by dots. These reflect the fact that at certain values of $m_{\tilde{g}}$ (and hence μ_1 and μ_2) level crossings occur. To understand this, we recall that the gluino decays occur only via the gaugino components of the mass eigenstates because the Higgs-fermion components couple only via the negligible Yukawa couplings. Thus, whenever a decay into several of the mass eigenstates is kinematically possible, the branching fraction is greatest into the states with the larger gaugino components. For example, in Fig. 1(a), consider the decays into charginos. For $m_{\tilde{g}}\lesssim 300$ GeV the lighter chargino state contained a large fraction of the gaugino whereas above 300 GeV, the chargino state with the larger gaugino content is the heavier one. The gaugino content of the state varies smoothly with the parameters μ_1 and μ_2 in the mass matrix, and hence the branching fraction varies smoothly over the transition from $\tilde{g}\to\tilde{W}_-$ to $\tilde{g}\to\tilde{W}_+$ decays. The apparent discontinuity in the branching fraction into $\tilde{W}_-$ is because we have labeled the states by their mass orderings rather than gaugino content. The same is true for the neutralinos, where

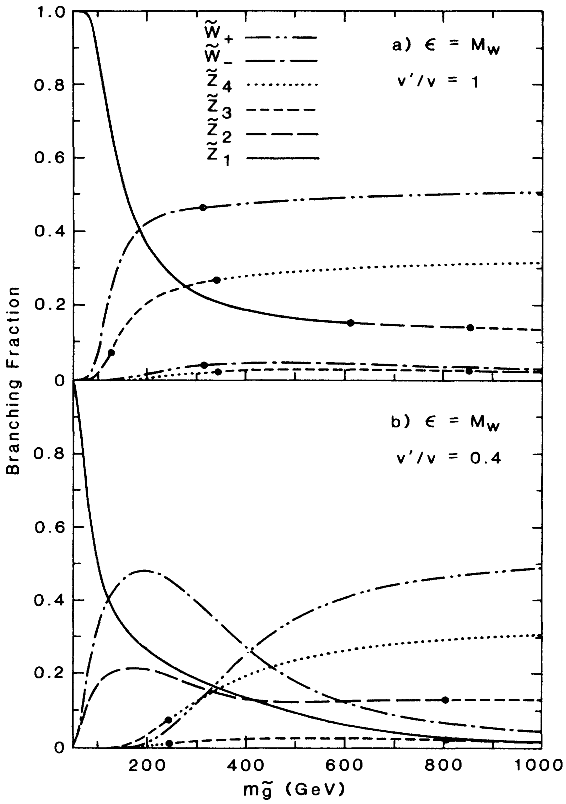

FIG. 1. Branching fractions of $\tilde g \to \bar q Q \tilde{\bar W}_i + \bar q Q \tilde W_i$ and $\tilde g \to q \bar q \tilde Z_i + Q \bar Q \tilde Z_i$ for $\epsilon \equiv 2m_1 = M_W$ and (a) $v'/v = 1$ and (b) $v'/v = 0.4$ for $q = d$, s, or b and $Q = u$ or c. The chargino states are labeled as $\tilde W_+$ (heavy chargino) and $\tilde W_-$ (light chargino). The four neutralino states are labeled according to their masses with $\tilde Z_1$ the lightest and $\tilde Z_4$ the heaviest neutralino. The large dots denote the level crossings discussed in the text. We assume $m_{\tilde q} = 2m_{\tilde g}$.

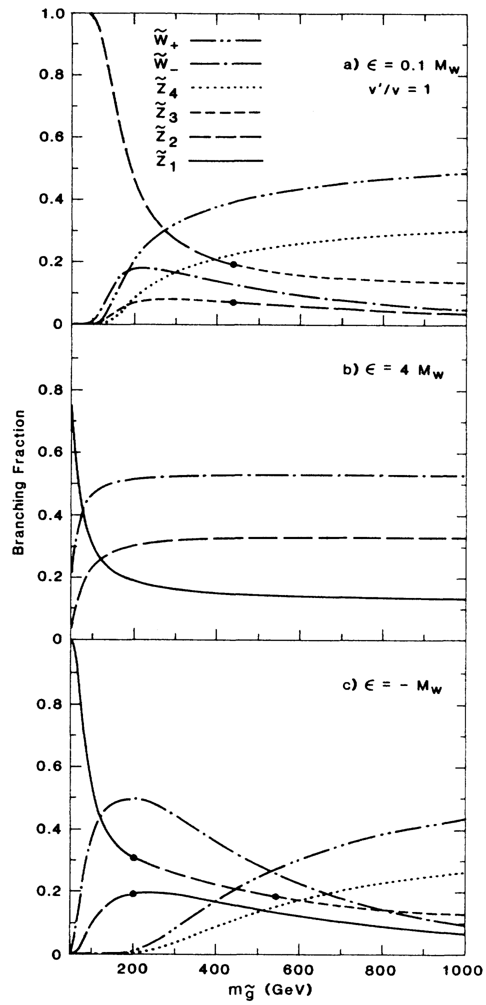

FIG. 2. Branching fractions of $\tilde g$ into chargino and neutralinos as in Fig. 1, except $v'/v = 1$ and $\epsilon \equiv 2m_1 =$ (a) $0.1 M_W$, (b) $4M_W$, and (c) $-M_W$.

the details are more complicated since there are four states.

(iv) The sum of the branching fractions for decays into charginos is roughly 50%, independent of all parameters, provided there is no kinematic suppression. This independence is easily understood if we recognize that the total of the chargino decays can be calculated from estimating the decays into λ_- whose couplings are just fixed by $SU(2) \times U(1)$ and SUSY and are independent of the model parameters.

(v) When $v'/v = 1$, the combination $(1/\sqrt{2})(h^0 + h'^0)$ is an eigenstate with mass $-2m_1$. The branching fraction into this state is essentially zero. Its ordering in terms of masses depends on the parameters, and so the mass eigenstate with vanishing branching fraction may be any one of the $\tilde Z_i$. For $v'/v \neq 1$ this is not an eigenstate. In fact, as seen from Table I, the mass eigenstates are always nontrivial mixtures of gauginos and Higgs fermions. Correspondingly, in Fig. 1(b), a heavy $\tilde g$ has a nonvanishing branching fraction into all the $\tilde Z_i$'s.

(vi) The gluino decays are dependent on all the parameters of the model. Even changing the sign of $2m_1$ significantly alters the decay patterns, as is reflected in the mixings shown in Table I.

(vii) Figures 1 and 2 do not give the correspondence with the masses of the neutralino and chargino states. Some idea of these may be obtained from Table I. The heavier states will cascade decay to the lighter ones. For heavy gluinos, the decays are dominantly into the heaviest chargino and neutralino [unless $2m_1$ is very large, as in Fig. 2(b), so that $\tilde W_+$, $\tilde Z_3$, and $\tilde Z_4$ are all heavy and Higgs-fermion-like]. From Table I we see that the masses of the heaviest chargino and neutralino considerably exceed those of the electroweak gauge bosons, so that their decays into these and the light charginos and neutralinos are kinematically allowed. Thus, the decay products of heavy gluinos are likely to contain $W^{\pm}$ and Z^0 bosons, which are an important experimental signature.

(viii) The gluino branching fractions for $v'/v = r$ are the same as those for $v'/v = 1/r$. For the neutralinos this follows because the gaugino contents of the neutralino is unaltered under this interchange. In the $\tilde{g}$ decays to $\tilde{W}_i$, the virtual $\tilde{d}_L$ and $\tilde{\bar{u}}_L$ occur via different handedness of the original gaugino λ [corresponding to the occurrence of the angles γ_L and γ_R in Eqs. (2.13)–(2.15)]; these L and R components switch under $r \to 1/r$, as discussed in (vii) of Sec. II. Since we have taken all scalar quarks to be degenerate, the branching fractions are also unaltered for $r \to 1/r$.

We now briefly discuss the decays of scalar quarks for the case when the decay $\tilde{q} \to q\tilde{g}$ is kinematically suppressed. The partial widths can be easily calculated using the couplings in Sec. II. We have

$$\Gamma(\tilde{q}_L \to q\tilde{Z}_i) = \frac{|A^q_{\tilde{Z}_i}|^2}{16\pi} m_{\tilde{q}_L} \left[1 - \frac{m_{\tilde{Z}_i}^2}{m_{\tilde{q}_L}^2}\right]^2 , \quad (3.4a)$$

$$\Gamma(\tilde{q}_R \to q\tilde{Z}_i) = \frac{|B^q_{\tilde{Z}_i}|^2}{16\pi} m_{\tilde{q}_R} \left[1 - \frac{m_{\tilde{Z}_i}^2}{m_{\tilde{q}_R}^2}\right]^2 , \quad (3.4b)$$

$$\Gamma(\tilde{q}_L \to q\tilde{W}_i) = \frac{|A^q_{\tilde{W}_i}|^2}{16\pi} m_{\tilde{q}_L} \left[1 - \frac{m_{\tilde{W}_i}^2}{m_{\tilde{q}_L}^2}\right]^2 , \quad (3.4c)$$

and

$$\Gamma(\tilde{q}_R \to q\tilde{W}_i) = 0 . \quad (3.4d)$$

The branching fractions into the various channels are shown in Figs. 3 and 4 for the case $\epsilon \equiv 2m_1 = M_W$ and $v'/v = 1$ and $v'/v = 0.4$, respectively. For definiteness, we have taken $m_{\tilde{q}} = m_{\tilde{g}}$ in the figure. This fixes μ_2 and μ_1 for a given scalar-quark mass. For the left-handed scalar quarks the qualitative features of the decays are similar to those for gluino decays. This is just because the gluino decays via virtual $\tilde{q}_L$ are weighted more than those through $\tilde{q}_R$ because the coupling constants of $\tilde{q}_L$ to the states tend to be larger. The right-handed scalar quark decays only to neutralinos since it has no couplings to the gaugino component of the charginos. We also see that, depending on its mass, the $\tilde{q}_R$ decays into one of the neutralinos with a branching fraction exceeding 90%. Moreover, for heavier scalar quarks, the favored decays are into heavier charginos and neutralinos, and so, as for heavy-gluino production, one would expect gauge bosons in a substantial fraction of their decays. We note, however, that since the decay of the right-handed scalar quark proceeds only via the λ_0 component of the gaugino [see Eq. (2.15)] it is clear from Table I that it decays into the heavier gauginos only if $m_{\tilde{g}}$ ($= m_{\tilde{q}}$) is really large.

Our discussion of scalar-quark branching fractions has up to this point been for $2m_1 = M_W$. The branching fractions are also quite sensitive to $2m_1$. For small values of $2m_1$, $\tilde{q}_L$ tends to decay into the heavier charginos whereas for $2m_1 = 4M_W$ almost all the decays are into $\tilde{W}_-$, $\tilde{Z}_1$, and $\tilde{Z}_2$. For the same reasons as we discussed in the gluino case, the sum of the chargino decays is, once again, almost independent of model parameters.

Finally, we comment on the case when v'/v changes from $v'/v = r$ to $1/r$. This interchanges the left- and

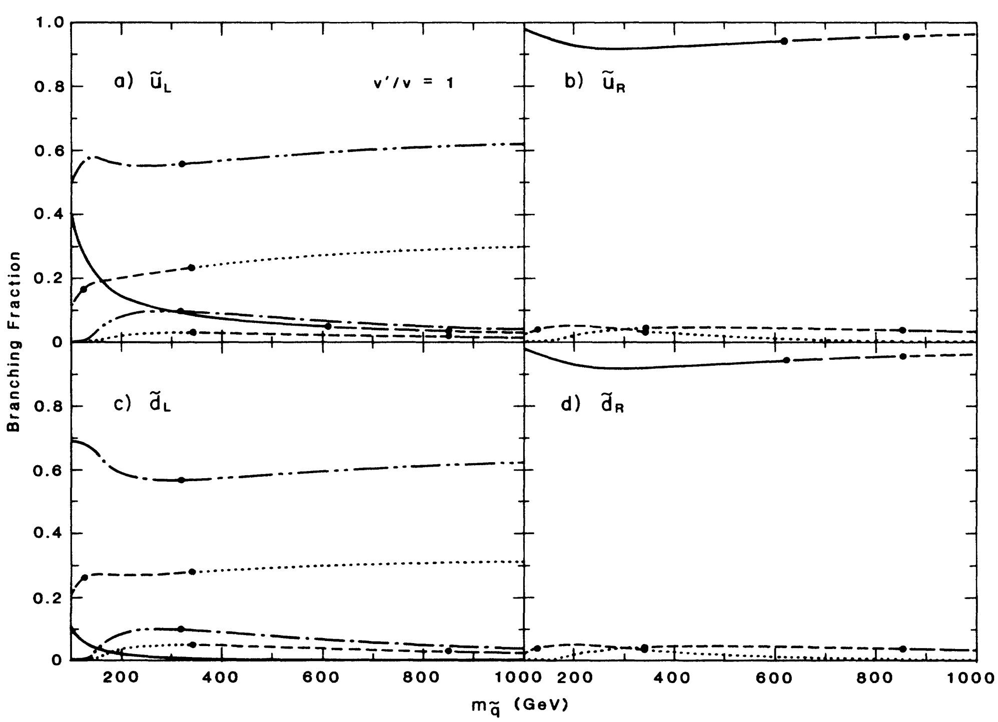

FIG. 3. Branching fractions of scalar quarks into gauginos for $m_{\tilde{q}} = m_{\tilde{g}}$. We assume $\epsilon \equiv 2m_1 = M_W$ and $v'/v = 1$, and give plots for (a) $\tilde{u}_L$, (b) $\tilde{u}_R$, (c) $\tilde{d}_L$, and (d) $\tilde{d}_R$. The curves are for $\tilde{q} \to q\tilde{W}_-$ (dot-dashed), $\tilde{q} \to q\tilde{W}_+$ (dot-dot-dashed), $\tilde{q} \to q\tilde{Z}_1$ (solid), $\tilde{q} \to q\tilde{Z}_2$ (short-dashed), $\tilde{q} \to q\tilde{Z}_3$ (long-dashed), and $\tilde{q} \to q\tilde{Z}_4$ (dotted).

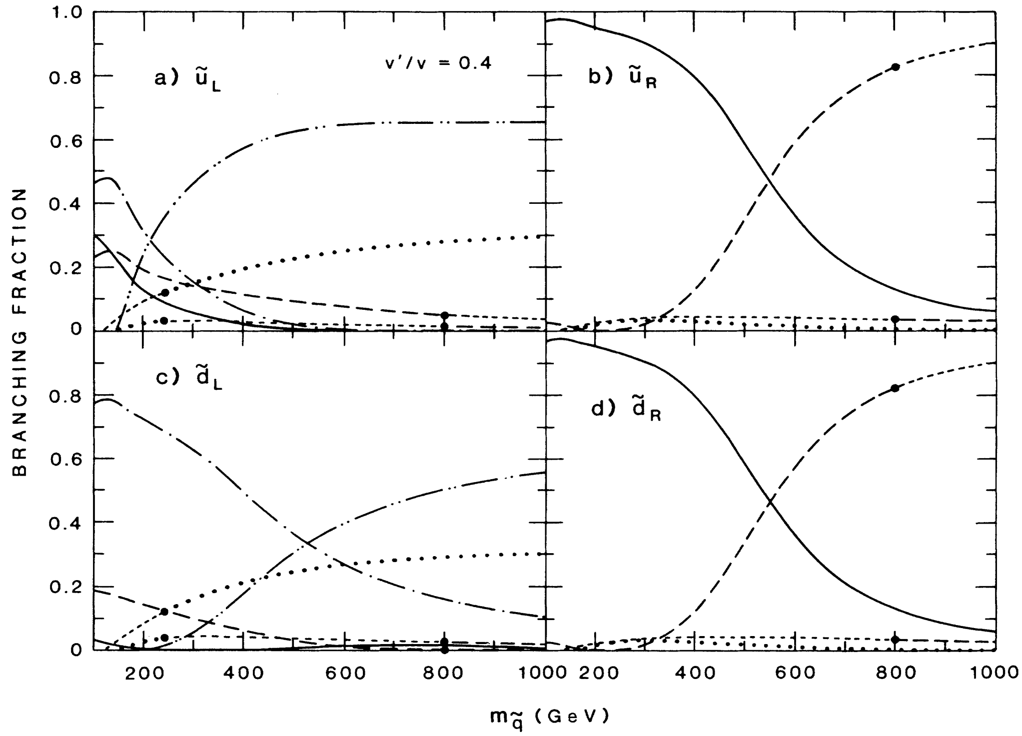

FIG. 4. Branching fractions for scalar quarks into gauginos as in Fig. 3, except $v'/v=0.4$.

right-handed chargino components but leaves the gaugino components of the neutralino unaltered in magnitude. Thus, the branching fraction for $\tilde{d}_L \to \tilde{W}_i u$ when $v'/v=r$ is equal to that for $\tilde{u}_L \to \tilde{W}_i d$ for $v'/v=1/r$ with the neutralino branchings remaining the same.

IV. EVENT RATES AND SIGNATURES

In this section, we discuss the event topologies that may be expected from production and decays of heavy gluinos and scalar quarks at a hadron supercollider. We focus on the case $m_{\tilde{q}}=2m_{\tilde{g}}$, so that scalar quarks decay via $\tilde{q}\to q\tilde{g}$. Cross sections for $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{g}$, and $\tilde{q}\tilde{q}$ pair production are already available in the literature.[7] Figure 5 gives cross sections based on the Eichten-Hinchliffe-Lane-Quigg[17] distributions with $\Lambda=0.2$ at pp colliders with $\sqrt{s}=40$ TeV (SSC) and $\sqrt{s}=10$ TeV (EHF). Gluino pairs dominate over $\tilde{q}\tilde{g}$ and $\tilde{q}\tilde{q}$ production. At the SSC, with an anticipated luminosity of 10^4 pb^{-1}/yr, the event rates are 4×10^8 gluino pairs for $m_{\tilde{g}}=200$ GeV and 10^5 gluino pairs for $m_{\tilde{g}}=1$ TeV; the rates at $\sqrt{s}=10$ TeV are a factor of 30–200 smaller for comparable luminosity.

A produced gluino rapidly decays into $\tilde{W}_i$ or $\tilde{Z}_i$, with the branching fractions given in Sec. III. We thus have $p\bar{p}\to\tilde{g}\tilde{g}\to q\bar{q}\tilde{G}+q\bar{q}\tilde{G}$ ($\tilde{G}=\tilde{W}_i$ or $\tilde{Z}_j$). A gluino pair event, therefore, consists of up to four jets plus a chargino-neutralino pair. In a substantial fraction of events, the decay products of each gluino may be in opposite hemispheres. For each gluino that results from scalar-quark decay. there is an additional quark which is very hard.

The numbers of such $\tilde{G}_i\tilde{G}_j+$ jets events expected annually at the SSC for two different gluinos masses and for $v'/v=1$ and 0.4 are given in Table II. For $\tilde{g}=250$ GeV, the production of lighter gauge-Higgs-fermions (GHF's) is much more copious than that for heavier GHF's. This is largely due to the small couplings of the heavy GHF's and not to the lack of phase space for the decay. Never-

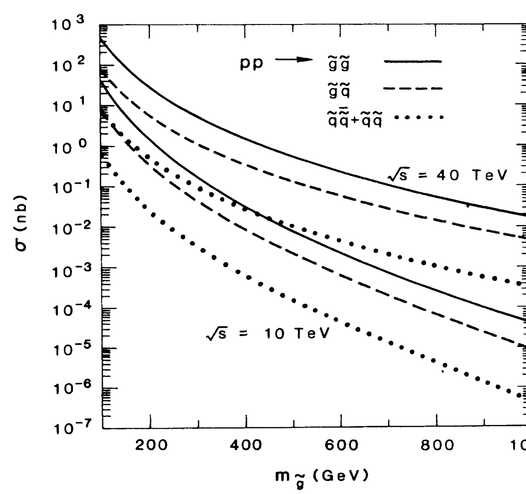

FIG. 5. Total cross sections for $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, and $\tilde{q}\bar{\tilde{q}}+\tilde{q}\tilde{q}$ production vs $m_{\tilde{g}}$ in pp collisions at $\sqrt{s}=10$ and 40 TeV. We assume $m_{\tilde{q}}=2m_{\tilde{g}}$ and assume six degenerate flavors of right and left scalar quarks.

theless, there are 10^6–10^7 events containing $\tilde{W}_+$ and ten times as many events containing $\tilde{W}_-$. For $m_{\tilde{g}}=750$ GeV, there are $\gtrsim 10^5$ $\tilde{W}_+$ events and a much smaller number of $\tilde{W}_-$ events. Moreover, in most of the $\tilde{W}_+$ events, in this case, the other $\tilde{G}$ is $\tilde{W}_+$ or $\tilde{Z}_4$ reflecting the fact that heavy gluinos preferentially decay into the heavy charginos and neutralinos. For the whole range of parameters considered in Table II less than about 5% of the events have both gluinos decaying into $\tilde{Z}_1$.

The signatures for heavy gluinos depend on how the heavy gauginos decay. We concentrate here on $\tilde{W}_+$ decays since $\tilde{g}\to q\bar{q}\tilde{W}_+$ is the dominant $\tilde{g}$ decay mode unless $2m_1$ is very large. The decay widths for $\tilde{W}_+$ into gauge bosons are given by

$$\Gamma(\tilde{W}_+\to\tilde{Z}_j W)=\frac{g^2}{32\pi m_{\tilde{W}_+}{}^3}\lambda^{1/2}(m_{\tilde{W}_+}{}^2,M_W{}^2,m_{\tilde{Z}_j}{}^2)$$
$$\times[2(|X^j_{(+)}|^2+|Y^j_{(+)}|^2)f(m_{\tilde{W}_+}{}^2,m_{\tilde{Z}_j}{}^2,M_W{}^2)-12m_{\tilde{W}_+}m_{\tilde{Z}_j}(|X^j_{(+)}|^2-|Y^j_{(+)}|^2)] \tag{4.1}$$

and

$$\Gamma(\tilde{W}_+\to\tilde{W}_-Z^0)=\frac{e^2}{128\pi m_{\tilde{W}_+}{}^3}(\cot\theta_W+\tan\theta_W)^2\lambda^{1/2}(m_{\tilde{W}_+}{}^2,M_Z{}^2,m_{\tilde{W}_-}{}^2)$$
$$\times[2(x^2+y^2)f(m_{\tilde{W}_+}{}^2,m_{\tilde{W}_-}{}^2,M_Z{}^2)-12(-1)^{\theta_++\theta_-}(y^2-x^2)m_{\tilde{W}_+}m_{\tilde{W}_-}]\,, \tag{4.2}$$

where

$$f(m_1{}^2,m_2{}^2,M^2)=m_1{}^2+m_2{}^2-M^2+\frac{(m_1{}^2-m_2{}^2)^2-M^4}{M^2} \tag{4.3}$$

and

$$\lambda(M^2,m_1{}^2,m_2{}^2)=M^4+m_1{}^4+m_2{}^4-2M^2m_1^2-2M^2m_2{}^2-2m_1{}^2m_2{}^2\,. \tag{4.4}$$

Figure 6 shows the $\tilde{W}_+$ branching fractions versus $m_{\tilde{g}}$.

(i) For $v'/v=1$, there is a range of gluino masses for which $\tilde{W}_+$ cannot decay into real gauge bosons. In this case, it decays via the three-body modes $\tilde{W}_+\to q\bar{q}'\tilde{Z}_i$ or $l\bar{\nu}\tilde{Z}_i$ and $\tilde{W}_+\to q\bar{q}\tilde{W}_-$ or $l\bar{l}\tilde{W}_-$.

(ii) For small values of $m_{\tilde{g}}$ ($\lesssim 250$ GeV) the branching fraction for the channel $\tilde{W}_+\to W\tilde{Z}_1$ is essentially 100%.

(iii) For intermediate values of $m_{\tilde{g}}$, the decay is essentially via $W_+\to W\tilde{Z}_1$ and $\tilde{W}_+\to W\tilde{Z}_2$ for all values of v'/v with the decay to $\tilde{Z}_2$ dominating over a wider range. The subsequent decays of $\tilde{Z}_1$ and $\tilde{Z}_2$ will be discussed shortly.

(iv) For heavy gluinos ($\gtrsim 700$ GeV), $\tilde{W}_+$ decays roughly equally into the modes $\tilde{W}_+\to W\tilde{Z}_i$ $[i=1,2,3$ $(m_{\tilde{Z}_4}>m_{\tilde{W}_+})]$ and $\tilde{W}_+\to Z\tilde{W}_-$.

(v) For intermediate values of $m_{\tilde{g}}\simeq 250$–700 GeV the qualitative features of these curves are not very sensitive to $2m_1$.

Thus, for a wide range of parameters there is a W boson present in the decays of $\tilde{W}_+$. For $m_{\tilde{g}}\gtrsim 600$–700 GeV, a Z boson may also be present. Also, the heavy neutralino would decay into a gauge boson and a lighter GHF.

Next, we consider the subsequent decays of the lighter GHF's which cannot decay into gauge bosons. The $\tilde{Z}_1$ is

TABLE II. The estimated number of $\tilde{W}_i\tilde{Z}_j$ pairs from $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, and $\tilde{q}\tilde{q}$ decays per 10^4 pb^{-1} of integrated luminosity expected per year at the SSC for two values of gluino masses (with $m_{\tilde{q}}=2m_{\tilde{g}}$) and for $v'/v=1$ and 0.4. The entries in the table need to be multiplied by 10^4 to get the number of GHF pairs. For $v'/v=1$ and $m_{\tilde{g}}=250$ GeV, the heavy GHF's are kinematically forbidden from decaying into gauge bosons so that their dominant decays are via the three-body modes except for $\tilde{Z}_2$ which is a pure Higgs fermion and so decays via $\tilde{Z}_2\to\tilde{Z}_1+\gamma$. For $v'/v\neq 1$ the decay of $\tilde{W}_+$ into gauge bosons is allowed for both values of $m_{\tilde{g}}$ (see Fig. 5); whereas, $\tilde{Z}_4$ decays into gauge bosons only for the $m_{\tilde{g}}=750$ GeV case. Finally, if $m_{\tilde{g}}=750$ GeV and $v'/v=1$, $\tilde{Z}_1$ is the lightest GHF and hence all events will contain photons as discussed in the text.

	$m_{\tilde{g}}=250$ GeV		$m_{\tilde{g}}=750$ GeV	
	$v'/v=0.4$	$v'/v=1$	$v'/v=0.4$	$v'/v=1$
$\tilde{W}_-\tilde{W}_-$	2828	2828	0.52	0.15
$\tilde{W}_-\tilde{W}_+$	754	314	6.21	3.31
$\tilde{W}_-\tilde{Z}_1$	2638	3519	0.41	
$\tilde{W}_-\tilde{Z}_2$	2387		1.79	1.10
$\tilde{W}_-\tilde{Z}_3$	126	3016	0.28	0.15
$\tilde{W}_-\tilde{Z}_4$	1131	126	4.00	2.21
$\tilde{W}_+\tilde{W}_+$	50.2	8.73	18.6	18.6
$\tilde{W}_+\tilde{Z}_1$	352	195	2.48	
$\tilde{W}_+\tilde{Z}_2$	318		10.8	12.4
$\tilde{W}_+\tilde{Z}_3$	16.8	168	1.66	1.66
$\tilde{W}_+\tilde{Z}_4$	151	6.98	24.0	24.8
$\tilde{Z}_1\tilde{Z}_1$	616	1095	0.08	
$\tilde{Z}_1\tilde{Z}_2$	1114		0.72	
$\tilde{Z}_1\tilde{Z}_3$	58.6	1877	0.11	
$\tilde{Z}_1\tilde{Z}_4$	528	78.2	1.60	
$\tilde{Z}_2\tilde{Z}_2$	504		1.55	2.07
$\tilde{Z}_2\tilde{Z}_3$	53.0		0.48	0.55
$\tilde{Z}_2\tilde{Z}_4$	478		6.94	8.28
$\tilde{Z}_3\tilde{Z}_3$	1.40	804	0.04	0.04
$\tilde{Z}_3\tilde{Z}_4$	25.1	67.0	1.07	1.10
$\tilde{Z}_4\tilde{Z}_4$	113	1.40	7.74	8.28

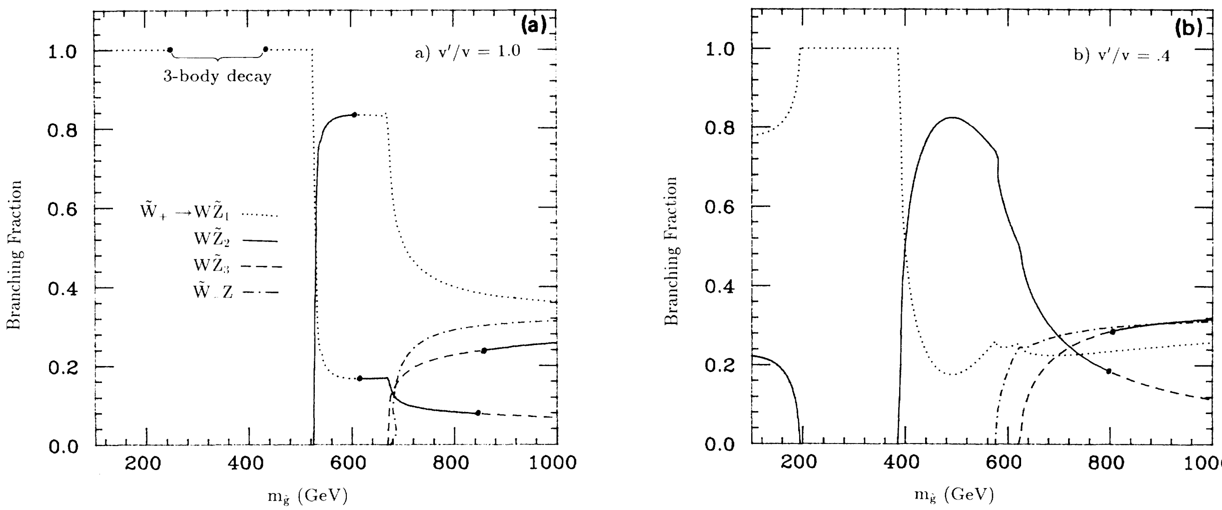

FIG. 6. Branching fractions for the decays of the heavy chargino $\tilde{W}_+$ as a function of $m_{\tilde{g}}$ for $\epsilon \equiv 2m_1 = M_W$ and (a) $v'/v = 1$ and (b) $v'/v = 0.4$. The SU(2) and U(1) gaugino masses are determined by $m_{\tilde{g}}$ as discussed in the text. The dots denote the level crossings for the charginos and neutralinos.

essentially stable since it is presumed to be the lightest SUSY particle. The other GHF's, $\tilde{W}_-$, $\tilde{Z}_2$, and $\tilde{Z}_3$ decay into $\tilde{Z}_1$+quark or lepton pairs.[18] An exception to this occurs for $v'/v = 1$ for whichever light neutralino is a pure Higgs fermion. If this Higgs fermion is not the lightest neutralino, it would decay into $\tilde{Z}_1 + \gamma$ via a one-loop graph.[19] If $\tilde{Z}_1$ is a Higgs fermion, the other GHF's would cascade into $\tilde{Z}_2$ via tree graphs. These will then decay into $\tilde{Z}_1 + \gamma$ via the loop graph just discussed. This leads to the conclusion that if the Higgs fermion is the lightest SUSY particle, there would be a photon in the final stage of the light GHF decays. Otherwise, the photon occurs only in the decay of the Higgs-fermion neutralino. If $v'/v \neq 1$, the neutralino states all contain substantial gaugino components (see Table I) so that they can all decay via tree graphs. For a detailed discussion of light neutralino decays, we refer to Komatsu and Kubo.[19]

Gluinos with masses up to $\sim$1 TeV are copiously produced at the SSC from gg and $q\bar{q}$ fusion, and also, to a smaller extent, via decays of scalar quarks. If $m_{\tilde{g}} \gtrsim 300$–$500$ GeV, they dominantly decay into heavy charginos and neutralinos which in turn decay into a lighter GHF. For a wide range of parameters, we have seen that $\tilde{W}_+$ decays into a neutralino and a W boson, with the neutralino usually decaying via the three-body mode into the lightest neutralino and quark or lepton pairs. For heavy gluinos the decays of $\tilde{W}_+$ into Z bosons are also present with a 30% branching fraction. The typical final state from each gluino would therefore contain hard jets, a gauge boson, and residual quarks or leptons. A typical gluino-pair event is illustrated in Fig. 7. Further, if $\tilde{Z}_1$ is a Higgs fermion, there will always be a photon present in the final state.[19] We have not studied the details of the final-state topologies and related questions such as whether the leptons or photons are isolated. Such issues are an important consideration regarding backgrounds to these complex events at the SSC, but are beyond the scope of this paper.

We emphasize, however, that because the escaping neutralino is produced via a cascade of decays rather than from the direct decay of the gluino, its transverse momentum may be considerably degraded. Furthermore, if any of the W bosons or other GHF's decay leptonically there will be neutrinos in the final state. For these reasons, the missing-p_T spectrum from heavy-$\tilde{g}$ events may be considerably softer than would be obtained from the naive assumption $\tilde{g} \to q\bar{q}\tilde{\gamma}$ with the $\tilde{\gamma}$ escaping detection. A detailed study via a Monte Carlo simulation is necessary before definitive conclusions can be drawn.

Although we have not shown the event rates for gaugino pairs for the case $m_{\tilde{q}} < m_{\tilde{g}}$, these can be easily estimated from the cross sections shown in Fig. 4 using the scalar-quark branching fractions shown in Fig. 3. The decays of $\tilde{q}_L$ are qualitatively similar to those of the gluino, and so one expects a substantial number of $\tilde{W}_+$'s from

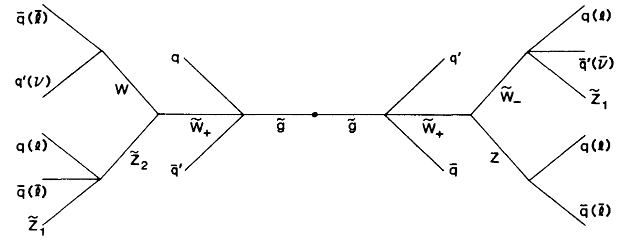

FIG. 7. A typical gluino-pair event for 0.8-TeV gluinos that may be produced at the SSC. We assume that both of the gluinos decay via $\tilde{g} \to q\bar{q}\tilde{W}_+$ [branching fraction $\sim(0.5)^2 = 0.25$]. The decay of the first $\tilde{W}_+$ occurs via $\tilde{W}_+ \to W\tilde{Z}_2$ (branching fraction $\sim$0.3) and of the other via $\tilde{W}_+ \to \tilde{W}_- Z^0$ (branching fraction 0.3). The $\tilde{Z}_2$ and $\tilde{W}_-$ then decay via the three-body modes. There are thus twelve quarks and leptons and two $\tilde{Z}_1$'s in this event. In the above we assume that none of the neutralinos is a pure Higgs fermion. For $v'/v = 1$, $\tilde{Z}_1$ is a Higgs fermion and hence the decay of $\tilde{Z}_2$ would be $\tilde{Z}_2 \to \gamma + \tilde{Z}_1$, whereas the $\tilde{W}_-$ still decays into $q\bar{q}\tilde{Z}_1$ or $l\bar{\nu}\tilde{Z}_1$.

their decays. The right-handed scalar quarks decay into neutralinos. Unless the scalar-quark mass is rather large, the decay is into the light ($\widetilde{Z}_1$ or $\widetilde{Z}_2$) neutralinos. Thus, for a large range of parameters, roughly half of the produced scalar-quarks will decay into heavy GHF's. Previous comments about the modification of the $\not{p}_T$ signatures made in the context of gluino decays apply equally well to the decays of scalar quarks.

V. SUMMARY AND CONCLUDING REMARKS

We have analyzed the decays of very heavy scalar quarks and gluinos relevant to supersymmetry searches at a hadron supercollider. For $m_{\tilde{g}} \gtrsim 0.3-0.5$ TeV, the preferred gluino decay is into heavy charginos and neutralinos. The GHF's from heavy-gluino decays then decay into vector bosons and lighter GHF's. These decay patterns give gluino signatures that are considerably more complex than those based on the $\tilde{g} \to q\bar{q}\tilde{\gamma}$. Similar remarks apply to scalar-quark decays.

Our main conclusions for heavy gluino and scalar-quark decay patterns are summarized in Figs. 1–3. The expected event rate for various gaugino pairs that may be expected annually from gluino decays at the SSC is shown in Table II. Decays of a 0.75-TeV gluino will result in almost 5×10^5 heavy GHF pairs. These GHF's will subsequently decay into gauge bosons and lighter GHF's. A typical cascade is $\tilde{g} \to q\bar{q}W_+ \to q\bar{q}Z\widetilde{W}_-$. If the Z^0 and $\widetilde{W}_-$ both decay into electrons and muons (combined branching fraction of $6\%\times22\%\sim1.5\%$) a gluino pair could lead to a few events containing six leptons just from this mode. The enormous rates for gluino (scalar-quark) production should enable us to identify some background-free signals. In addition to six lepton events, there would be other n lepton$+m$ jet$+\not{p}_T$ events ($n \lesssim 4$) with considerably larger rates. Furthermore, if the signals that are observed are to be identified as coming from gluinos (or scalar quarks), all the topologies possible from the various events shown in Table II should be present. There might also be a large number of events with a hard γ, although it is not clear whether the photons would be identifiable. A Monte Carlo simulation of the various event possibilities and a detailed discussion of the distributions is the next step that should be undertaken.

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