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Model dependence of the chargino mass bound from the CERN collider data

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We examine the validity of the limit ($m_{\tilde{W}} \gtrsim 40$ GeV) on the chargino mass that was inferred from the UA1 bound ($m_L \geq 41$ GeV) on the sequential heavy-lepton mass. This limit was obtained under the assumption that the supersymmetry-breaking gaugino masses are small ($m_{\tilde{g}} \lesssim 50$ GeV) so that the lightest neutralino ($\tilde{Z}_1$) is dominantly a photino with $m_{\tilde{\gamma}} < 8$ GeV. For larger gluino masses, we find that there is a substantial region of parameter space of the minimal supersymmetric model where $(m_{\tilde{W}} - m_{\tilde{Z}_1})$ is rather small so that $m_{\tilde{W}}$ as small as 20–25 GeV is not excluded by the CERN collider data. Multilepton signals from gaugino decays are also commented upon.

The decays of the weak bosons $W^{\pm}$ (Z^0) can serve as a useful laboratory for probing the existence of new weakly interacting particles that can be kinematically produced via these decays. Even in the rather messy environment of hadronic collisions, such decays may lead to clearly identifiable signatures. Already, the nonobservation of the decays $W \to L\nu_L$ and $W \to \tilde{e}_L \tilde{\nu}_L$ have led the UA1 Collaboration to infer the limits[1,2]

$$m_L \gtrsim 41 \text{ GeV} \quad (m_{\nu_L} = 0) \tag{1}$$

and

$$m_{\tilde{e}_L} \simeq m_{\tilde{\nu}} \gtrsim 30 \text{ GeV} \quad (m_{\tilde{\gamma}} = 0) \; . \tag{2}$$

From the absence of the decay $Z \to \tilde{W}\overline{\tilde{W}}$, the UA2 Collaboration have inferred the limit[3]

$$m_{\tilde{W}} \gtrsim 45 \text{ GeV} \quad (m_{\tilde{\nu}} \lesssim 20 \text{ GeV}) \tag{3}$$

on the masses of the W-ino. The limit (3) has been derived assuming that (i) $\tilde{W}$ is a pure gaugino, the supersymmetric partner of the W boson, and (ii) the scalar neutrino ($\tilde{\nu}$) is the only sfermion lighter than the $\tilde{W}$ so that the W-ino dominantly decays via $\tilde{W} \to \tilde{\nu}_l l$ ($l = e$, μ, or τ). Neither of these assumptions is likely to be valid in most supergravity models.[4] Assumption (ii) is especially crucial in obtaining the bound (3) since it follows that $\frac{4}{9}$ of the decays of the $\tilde{W}\overline{\tilde{W}}$ pair result in almost background-free[5] acollinear lepton pair (e^+e^-, $\mu^+\mu^-$, and $e^{\pm}\mu^{\mp}$) events with little hadronic activity. In comparison, for the generic case where the leptonic and hadronic decays of the $\tilde{W}$ have the same kinematics (this would be the case if all the sfermions are heavier than the W boson), only $\frac{1}{20}$ of the $\tilde{W}\overline{\tilde{W}}$ events result in the clean signal of the type discussed above.

Some time ago, we reported the results of a detailed analysis[6] of both the hadronic and leptonic signals resulting from the decays of the gauge bosons $W^{\pm}$ and Z^0 into charginos and neutralinos. In this analysis we did not rely on any special assumption about the sfermion masses. Furthermore, we did not assume that the chargino and neutralinos were pure gauginos; instead, we use the minimal supergravity model[4] with general soft supersymmetry- (SUSY-) breaking terms as a guide to obtain the masses and mixings of the mass eigenstates in the gaugino-Higgsino sector. This reduces, for example, the $Z \to \tilde{W}\overline{\tilde{W}}$ cross section from the simple no-mixing case. A similar analysis has also been performed by the authors of Ref. 7.

One assumption that has been made in these analyses is that the lightest neutralino state ($\tilde{Z}_1$) is dominantly a photino ($\tilde{\gamma}$) with $m_{\tilde{\gamma}} \ll M_W$. At this point, we recall that the chargino and neutralino mass matrices are determined in terms of three parameters.[4] In the notation of Ref. 6, these are (i) the supersymmetric Higgsino mass $2m_1$, (ii) the ratio v'/v of the vacuum expectation values of the two Higgs fields H and H' that give masses to the $T_3 = +\frac{1}{2}$ and $T_3 = -\frac{1}{2}$ fermions, respectively, and (iii) the SUSY-breaking gaugino mass. [As in Ref. 6 we assume that SU(3), SU(2), and U(1) gaugino masses are equal at the unification scale so that we may eliminate the electroweak gaugino masses in favor of the gluino mass $m_{\tilde{g}}$.] Also, only the relative sign between $2m_1$ and the gaugino mass is relevant so that we can take the gaugino mass to be negative [i.e., the gluino mass is minus the SU(3) gaugino mass] without loss of generality. Unless $2m_1 \simeq 0$, where a Higgsino state becomes light, the assumption $\tilde{Z}_1 \approx \tilde{\gamma}$ is the equivalent to $m_{\tilde{g}} \lesssim 50$ GeV (Ref. 4). In this case, the existence of a chargino state with $m_{\tilde{W}} < M_W$ and another neutralino ($\tilde{Z}_2$) state with $m_{\tilde{Z}_2} < M_Z$ is guaranteed on the basis of rather general considerations.[8]

The main conclusions of the analysis of Ref. 6 are summarized as follows. (1) For the case $m_{\tilde{\nu}} < m_{\widetilde{W}} < m_{\tilde{l}}, m_{\tilde{q}}$ as assumed in the analysis of the UA2 Collaboration, the nonobservation of acollinear dilepton events at the CERN collider would make it possible to exclude the existence of $\widetilde{W}$ with $m_{\widetilde{W}} < 45$ GeV [see Eq. (3)] even after taking into account the suppression of the $\widetilde{W}$-pair production rate due to the mixing. (2) For the case where the decays of $\widetilde{W}$ and $\widetilde{Z}_2$ (referred to as $\widetilde{Z}$ in Ref. 6) into sfermions are kinematically forbidden,[9] the nonobservation of quiet trilepton (from $W \to \widetilde{W}\widetilde{Z}_2$) and acollinear dilepton (from $W \to \widetilde{W}\widetilde{Z}_2$ and $Z \to \widetilde{W}\overline{\widetilde{W}}$) events at the CERN Collider would make it possible to rule out $\widetilde{W}$ and $\widetilde{Z}_2$ masses in the region $M_W > m_{\widetilde{W}} + m_{\widetilde{Z}_2}$. Moreover, it was shown that the hadronic decays of $\widetilde{W}$ and $\widetilde{Z}_2$ produced from $W \to \widetilde{W}\widetilde{Z}_{1,2}$ and $Z \to \widetilde{W}\overline{\widetilde{W}}$ result in a large rate for jet(s)+missing transverse-momentum ($\not{p}_T$) events similar to those expected from the hadronic decay of a sequential heavy lepton produced via $W \to L\nu_L$. It was further shown that the UA1 limit (1) translates to a limit

$$m_{\widetilde{W}} \gtrsim 40 \text{ GeV} \tag{4}$$

subject only to the validity of the assumption of small gaugino masses discussed in the previous paragraph.

The purpose of this study is to examine the validity of the bound (4), as we vary the three parameters that determine the masses and the couplings of the charginos and neutralinos. Most importantly, we examine the effect of increasing $m_{\tilde{g}}$ to large values[10] so that $\widetilde{Z}_1$ is no longer a photinolike state. We note here that the UA1 Collaboration has recently reported[11] the bound $m_{\tilde{g}} \gtrsim 53$ GeV so that it is almost necessary to relax our earlier assumption on the smallness of gaugino masses which, in turn, was motivated by other theoretical considerations.[12]

We note here that unlike the light-photino case[8] considered earlier, there is no general theorem that guarantees the existence of $\widetilde{W}$ and $\widetilde{Z}_2$ lighter than the W and Z^0 bosons, respectively. For the minimal model, however, it has recently been shown[13] that the smallness of $m_{\widetilde{Z}_1}$ is sufficient to ensure the existence of $\widetilde{W}$ ($\widetilde{Z}_2$) with a mass smaller than M_W (M_Z).

There are two main effects that we have to take into account in our analysis. First, the masses and the mixings of the charginos and neutralinos have to be computed for general values of the model parameters in order to determine the partial widths for the decays $W \to \widetilde{W}\widetilde{Z}_{1,2}$, $Z \to \widetilde{W}\overline{\widetilde{W}}$, and $Z \to \widetilde{Z}_2\widetilde{Z}_{1,2}$ (Ref. 14). We use the formulas of Ref. 13 in our computation of the "gaugino" production cross sections which differ from those in our earlier calculation due to (i) differences in the relative values of $m_{\widetilde{W}}$, $m_{\widetilde{Z}_1}$, and $m_{\widetilde{Z}_2}$, and (ii) altered couplings due to different admixtures of the current eigenstates in the $\widetilde{W}$ and $\widetilde{Z}_{1,2}$. The other important factor is the effect of the altered kinematics on the fraction of events that pass the cuts and triggers that we had used to simulate the UA1 event selection criteria. For a example, for a given $\widetilde{W}$ ($\widetilde{Z}_2$) mass, we expect that the $\not{p}_T$ and the p_T of the jets resulting from the decays $\widetilde{W} \to q\bar{q}\widetilde{Z}_1$ ($\widetilde{Z}_2 \to q\bar{q}\widetilde{Z}_1$) become smaller for heavier $\widetilde{Z}_1$ so that the fraction of events passing the cuts is reduced. The effect of increasing $m_{\widetilde{Z}_1}$ on the cut cross section for the UA1 detector has already been considered in Ref. 15 for $\widetilde{Z}_1 = \tilde{\gamma}$.

We proceed by first considering the allowed values of $m_{\widetilde{Z}_1}$ for fixed values of $m_{\widetilde{W}}$ as the model parameters ($2m_1, m_{\tilde{g}}, v'/v$) are varied. The results are shown in Fig. 1 on the $m_{\tilde{g}}$ vs $2m_1$ plane for three selected values of v'/v: (a) 1, (b) 0.5 or 2, and (c) 0.2 or 5. We see that except for a rather limited region of the parameter space in the vicinity of $2m_1 = -50$ GeV, $m_{\widetilde{W}} \lesssim 40$ GeV implies that $m_{\widetilde{Z}_1}$ is smaller than 20 GeV. If we further require $m_{\widetilde{Z}_1} < m_{\widetilde{W}}$ (Ref. 16), a substantial part of this region is already excluded as shown by the diagonally shaded area in Fig. 2. Also, it is clearly seen that in the region of parameter space considered in earlier analyses,[6,7] $m_{\widetilde{Z}_1} < 10$ GeV.

It is interesting to note that unless $\widetilde{W}$ is found at CERN LEP II, where $\widetilde{W}$'s with masses up to 80 GeV are detectable,[17] $m_{\widetilde{Z}_1} \gtrsim 30$–$40$ GeV follows except for the small region of parameter space with $m_{\tilde{g}} < 200$ GeV and $v'/v \simeq 1$. Also, rather conservative estimates suggest that the Fermilab Tevatron will probe gluino masses of up to 150 GeV in its first two years of operation.[18] Thus, at least within the framework of the minimal model, unless supersymmetry is discovered by the time the data from LEP II is analyzed, we would be forced to conclude that $m_{\widetilde{Z}_1} \gtrsim 30$–$40$ GeV except for a relatively tiny region of parameter space around $v'/v \simeq 1$ and $m_{\tilde{g}} \simeq 200$ GeV.

Before turning to the details of the dependence on the model parameters of the $\widetilde{W}$ mass bound that is suggested by the nonobservation[1] of a significant excess of $\not{p}_T$ events in the 1983–1985 CERN collider data sample, we briefly review how the bound $m_{\widetilde{W}} \gtrsim 40$ GeV was obtained in our earlier analysis.[6] There, a parton-level Monte Carlo generator was used to simulate the $\not{p}_T$ events resulting from the hadronic decays of $\widetilde{W}$ and $\widetilde{Z}_2$ for the UA1 acceptance and trigger conditions. These are described in detail in Ref. 6. In this computation the production and decays of the gauginos were calculated with the masses and mixings as obtained in the framework of the minimal model but for small SU(2)×U(1) gaugino masses. In order to obtain the limit (4), we use the sequential heavy-lepton bound, $m_L \gtrsim 41$ GeV obtained by the UA1 Collaboration. That is, we compare the parton-level cross sections for $\not{p}_T$ events from gauginos with that from heavy leptons under the same trigger and acceptance conditions. We then require that the gaugino cross section be smaller than the heavy-lepton cross section (σ_0) for $m_L = 41$ GeV. This yields the limit $m_{\widetilde{W}} \gtrsim 40$ GeV for $m_{\widetilde{Z}_1} \gtrsim 8$ GeV (Ref. 19). The point $2m_1 = 210$ GeV, $m_{\tilde{g}} = 53$ GeV, and $v'/v = 1$ in Fig. 2(a) corresponds to this bound.

Instead of repeating the time-consuming event simulation to study the sensitivity of this limit to the model parameters, we have adopted the following procedure,

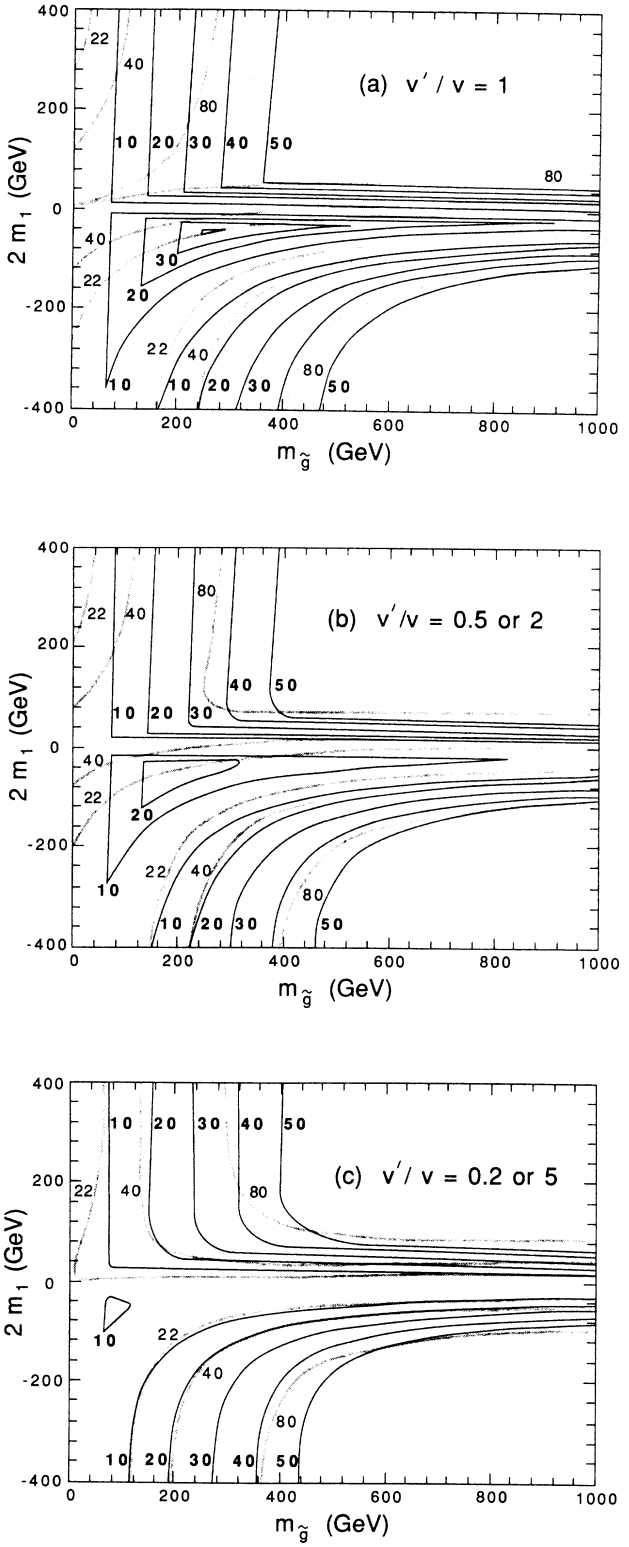

FIG. 1. A plot of the lightest neutralino ($\tilde{Z}_1$) and the lightest chargino ($\tilde{W}$) mass contours in the $m_{\tilde{g}}$ vs $2m_1$ (supersymmetric Higgsino mass) plane. We show contours for $m_{\tilde{W}}=22$, 40, 80 GeV by shaded lines and those for $m_{\tilde{Z}_1}=10$, 20, 30, 40, 50 GeV by solid lines. We show plots for (a) $v'/v=1$, (b) $v'/v=0.5$ or 2, and (c) $v'/v=0.2$ or 5, where v'/v is the ratio of the two Higgs-field vacuum expectation values.

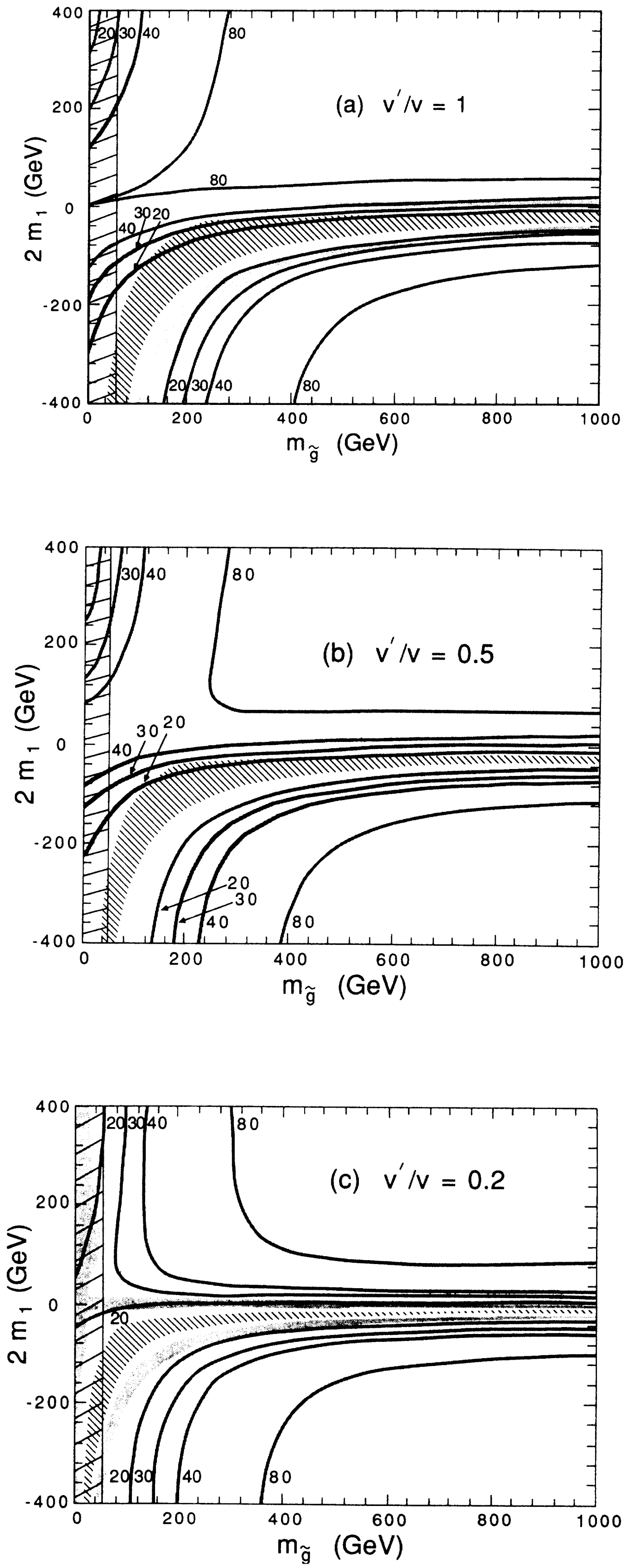

FIG. 2. A plot of excluded regions in the $m_{\tilde{g}}$ vs $2m_1$ plane for (a) $v'/v=1$, (b) $v'/v=0.5$, and (c) $v'/v=0.2$. The region excluded by the present analysis is shown by the shaded area. Requiring $m_{\tilde{Z}_1}<m_{\tilde{W}}$ excludes the region shaded by diagonals. The UA1 bound $m_{\tilde{g}}>53$ GeV is also shown. For reference, we show contours of $m_{\tilde{W}}=20$, 30, 40, 80 GeV.

which we believe yields an excellent approximation to the real situation.

(1) We use the event generator of Ref. 6 to extract the dependence of the "cut" cross section on the masses of $\tilde{W}$, $\tilde{Z}_1$, and $\tilde{Z}_2$ keeping all coupling constants fixed. There are two reasons for its change. First, there is the dependence of the partial widths for the decays $W \rightarrow \tilde{W}\tilde{Z}_i$ and $Z \rightarrow \tilde{W}\bar{\tilde{W}}$ on these masses. This is, of course, simple to compute. The second much more complicated effect (which is the reason for the Monte Carlo simulation) is the complex dependence of the effectiveness of the cuts and triggers on the masses. We isolate this later mass dependence by fixing the gauge-boson partial decay widths and calling the resulting suppression factor "the efficiency function." In principle, this efficiency function depends on the kinematics of the reaction so that there is a different function for each of the reactions, $W \rightarrow \tilde{W}\tilde{Z}_1$, $Z \rightarrow \tilde{W}\bar{\tilde{W}}$, and $W \rightarrow \tilde{W}\tilde{Z}_2$. Also each of these functions depends on all the gaugino masses. From our Monte Carlo analysis, we find, however, that these efficiency functions are very well represented by the functions $f(x = m_{\tilde{Z}_1}/m_{\tilde{W}})$ For $W \rightarrow \tilde{W}\tilde{Z}_1$,

$$f(x) = \begin{cases} 1 - 2.7x & \text{for } 0 < x < 0.31 \ , \\ 0.41 - 0.77x & \text{for } 0.31 < x < 0.53 \ ; \end{cases} \tag{5a}$$

for $Z \rightarrow \tilde{W}\bar{\tilde{W}}$,

$$f(x) = \begin{cases} 1 - 3.6x & \text{for } 0 < x < 0.25 \ , \\ 0.25 - 0.59x & \text{for } 0.25 < x < 0.42 \ ; \end{cases} \tag{5b}$$

and for $W \rightarrow \tilde{W}\tilde{Z}_2$,

$$f(x) = \begin{cases} 1 - 2.7x & \text{for } 0 < x < 0.32 \ , \\ 0.44 - 0.96x & \text{for } 0.32 < x < 0.46 \ . \end{cases} \tag{5c}$$

These efficiency functions are normalized at $f(x=0)=1$ and they vanish for x greater than the values quoted.

(2) Next, we compute the total rates of $\tilde{W}$ and $\tilde{Z}_2$ production from the processes $W \rightarrow \tilde{W}\tilde{Z}_{1,2}$, $Z^0 \rightarrow \tilde{W}\bar{\tilde{W}}$, and $Z^0 \rightarrow \tilde{Z}_{1,2}\tilde{Z}_2$ using the formulas of Ref. 13 which are valid for all values of model parameters. This amounts to neglecting the nonresonant squark-exchange contributions as well as the off-mass-shell $W^{\pm}$ and Z^0 contributions to gaugino pair production which have been shown to be negligible.[6]

(3) We next obtain the uncut $\not{p}_T$ cross section from gauginos by multiplying the rate in (2) above by appropriate factors of the hadronic branching fractions for $\tilde{W}$ and $\tilde{Z}_2$. For $\tilde{W}$, we take this to be $\frac{2}{3}$ independent of the $\tilde{W}$ mass since for sfermion masses greater than about 100 GeV, virtual W exchange dominates the $\tilde{W}$ decay.[6] For the decay $\tilde{Z}_2 \rightarrow \tilde{Z}_1 f\bar{f}$ $(f = q, l, \nu)$, we have made a new calculation for the $\tilde{Z}_2$ decay retaining the effects of virtual Z (Ref. 20), $\tilde{f}_L$, and $\tilde{f}_R$ exchanges. There are five Feynman graphs contributing to each decay. Virtual Z contributions which were neglected in Ref. 6 can be important when the $\tilde{Z}_1$ and $\tilde{Z}_2$ contain substantial Higgsino components and may dominate sfermion exchanges for heavy sfermions. For definiteness, we have taken the sfermion mass to be max(200 GeV, $m_{\tilde{g}}$). The decay $\tilde{Z}_2 \rightarrow \tilde{W} f \bar{f}\,'$ is important[6] only in a limited region of parameter space for $m_{\tilde{g}} \gtrsim 400$ GeV and $v'/v \simeq 1$. For the case where the virtual Z exchange is important in $\tilde{Z}_2$ decay, this decay mode is negligible. Since the decay mode $\tilde{Z}_2 \rightarrow \tilde{W} f \bar{f}\,'$ was not included in the simulation of Ref. 6, we have conservatively excluded its contribution to the $\not{p}_T$ cross section, although we have retained it in the compilation of the various branching fractions for the $\tilde{Z}_2$ decay.

(4) Finally, we obtain the $\not{p}_T$ cross section with the effect of the cuts and triggers by multiplying the uncut $\not{p}_T$ cross section obtained above by the appropriate efficiency function given by Eq. (5) and a normalization factor to reproduce the results of Ref. 6. We use the same efficiency function for $Z \rightarrow \tilde{Z}_2\tilde{Z}_1$ as for $W \rightarrow \tilde{W}\tilde{Z}_1$, and again, the same one for $Z \rightarrow \tilde{Z}_2\tilde{Z}_2$ as for $Z \rightarrow \tilde{W}\bar{\tilde{W}}$ as these reactions have similar kinematics. Our procedure effectively assumes that the effect of the cuts and triggers is dominantly governed by the kinematics of the process and is insensitive to the change of the matrix element due to the changes of the couplings. We thus obtain the "cut" cross section for any point in the three-dimensional parameter space. We then require that this cross section be smaller than σ_0, that yielded the UA1 bound (1).

The results of this analysis are shown in Fig. 2. The diagonally shaded region where $m_{\tilde{W}} < m_{\tilde{Z}_1}$ is excluded on the basis of cosmological considerations,[16] since we assume that $m_{\tilde{\nu}} > m_{\tilde{W}}$ in this analysis. We reemphasize that if the sneutrino is light, the absence of acollinear e^+e^-, $\mu^+\mu^-$, and $e^{\pm}\mu^{\mp}$ events at CERN and/or DESY PETRA rule out[6] this region of parameter space anyway. The remaining gray shaded region is the region that can be excluded from the nonobservation of $\not{p}_T$ events in the CERN Collider data.

We note the following features.

(i) For small gaugino masses, we reproduce the analysis of Ref. 6 so that the bound $m_{\tilde{W}} > 40$ GeV obtained earlier[6,7] is valid. Most of this region has since been excluded by the UA1 bound[11] $m_{\tilde{g}} \gtrsim 53$ GeV, which is also shown in Fig. 2.

(ii) For larger values of $m_{\tilde{g}}$, we see that the bound on $m_{\tilde{W}}$ is considerably weaker. This is mostly an effect of the increase in $m_{\tilde{Z}_1}$ and the corresponding reduction in both $\not{p}_T$ and the energy left over for the quarks to form jets according to the UA1 algorithm. This is also the reason for the gap between the region excluded by the cosmological constraint $m_{\tilde{W}} > m_{\tilde{Z}_1}$ and this analysis, i.e., in this gap, $m_{\tilde{Z}_1}$ is only slightly smaller than $m_{\tilde{W}}$. We note that although this gap is in the "PETRA region"[21] $m_{\tilde{W}} < 22$ GeV, only a fraction of the gap can be excluded even at e^+e^- colliders due to the softness of the decay products of the $\tilde{W}$ (and the corresponding increase in the backgrounds) when $m_{\tilde{Z}_1} \simeq m_{\tilde{W}}$.

(iii) We note that for negative values of $2m_1$ there are regions of the parameter space that are not excluded by this analysis even though $m_{\tilde{W}}$ is light ($\lesssim 30$ GeV) and $m_{\tilde{Z}_1}$ is only about 10 GeV (see Figs. 1 and 2). The reason for this is that $m_{\widetilde{Z}_1}/m_{\widetilde{W}}$ is rather large in this domain ($\simeq 0.5$), so that the p_T of the quarks from the decay $\widetilde{W}\to\widetilde{Z}_1 f\bar{f}$ is too soft for them to satisfy the UA1 trigger conditions and that the $\mathbf{p}_T$ of two $\widetilde{Z}_1$'s tend to cancel to leave smaller net $\not{p}_T$. This effect is clearly seen in Eq. (5), where all the efficiency functions practically vanish at $x=m_{\widetilde{Z}_1}/m_{\widetilde{W}}=0.5$. We expect that the PETRA bound ($m_{\widetilde{W}}\gtrsim 22$ GeV) (Ref. 21) applies in this region since the ratio $m_{\widetilde{Z}_1}/m_{\widetilde{W}}\simeq 0.5$ is not a big obstacle for e^+e^- experiments. In this region of the parameter space, $\widetilde{W}$'s with a mass up to 25 GeV may be detectable at KEK TRISTAN.

(iv) As v'/v is changed from unity[22] the gaugino mass spectrum remains the same under the exchange $v'/v\leftrightarrow v/v'$ and the excluded region in the case of small gluino masses extends to smaller values of $|2m_1|$. This is a reflection of the fact that within the minimal model with small gaugino masses, the maximum allowed value of $m_{\widetilde{W}}$ decreases[23] sharply as v'/v deviates from 1 [see Figs. 1(b) and 1(c)]. More importantly, we see that for the case of very small or very large values of v'/v [Fig. 2(c)], charginos with masses well below 20 GeV are not excluded *by this analysis.* This is due to the fact that throughout most of the parameter space, $m_{\widetilde{Z}_1}>0.5m_{\widetilde{W}}$. Although such small or large values of v'/v are unlikely in current supergravity models, we find it useful to examine the parameter dependence of our bound in a wide range of the parameter space.

(v) We have checked that the excluded region shown in Fig. 2 is very insensitive to the hadronic branching fraction of $\widetilde{Z}_2$. This is because $\widetilde{Z}_2$ decays contribute only a small amount to the $\not{p}_T$ cross section at the limit of observability. Our results are, therefore, insensitive to the exact value of the sfermion masses [our default choice was $m_{\tilde{f}}=\max(200\text{ GeV}, m_{\tilde{g}})$] provided only that sfermions are all heavy.

Before concluding this discussion, it is worth remarking that we have included only the hadronic decays of $\widetilde{W}$ and $\widetilde{Z}_2$ in obtaining the $\not{p}_T$ cross section used in obtaining the excluded region in Fig. 2. As discussed in Ref. 6, there is a substantial cross section for "monojets" from the case when one of the gauginos decays hadronically and the other leptonically where the leptons remain unidentified. In this sense, our delineation of the excluded region is somewhat conservative.

Finally, we remark on the multilepton signals that can result from $\widetilde{W}$ and $\widetilde{Z}_2$ decays. In the region of small gluino masses, it was shown[6] that the leptonic decay of both the $\widetilde{W}$ and $\widetilde{Z}_2$ would lead to spectacular trilepton and acollinear dilepton$+\not{p}_T$ events essentially free from hadronic activity. It was argued that a handful of these clean events would already be present in the accumulated CERN data sample. Moreover, it was emphasized that with the advent of the antiproton accumulator at CERN (ACOL) and the Fermilab Tevatron, these clean multilepton signals would lead to an unmistakable identification of $\widetilde{W}$ and $\widetilde{Z}_2$ provided $M_W>m_{\widetilde{W}}+m_{\widetilde{Z}_2}$.

As we move away from the small gaugino mass region, we find that $m_{\widetilde{Z}_2}-m_{\widetilde{W}}$ can become rather large[13] so that the decays $W\to\widetilde{W}\widetilde{Z}_2$, and hence the trilepton signals, may be kinematically suppressed for $m_{\widetilde{W}}$ as small as 30 GeV. This is the case when $\widetilde{Z}_1\sim$ Higgsino ($|2m_1|\ll m_{\tilde{g}}$) for all values of v'/v and also in the hyperbola-shaped shaded region of Fig. 2 where $\widetilde{Z}_1$ is a complicated mixture of the photino, the Z-ino, and the Higgsinos.[13] Furthermore, in the region of small $|2m_1|$, the $\widetilde{W}$ is dominantly a Higgsino so that the $\Gamma(Z\to\widetilde{W}\overline{\widetilde{W}})$ is only about one-third (isodoublet rather than isotriplet couplings to Z^0) that for the cases where $\widetilde{W}$ contains a large gaugino component. Thus along the band $2m_1\sim 0$ or in the region of very large $m_{\tilde{g}}$, even the dilepton signals may be suppressed to $\frac{1}{3}-\frac{1}{4}$ the level of those presented in Ref. 6. In spite of this, we believe that these signals will be observable with increased luminosity available with the turn on of ACOL and the Tevatron, assuming a reasonable efficiency for lepton detection. As there is no experimental analysis of multilepton$+\not{p}_T$ events comparable to the monojet analysis,[1,3,11] we will not discuss this potentially clean signal any further at the present time.

In summary, we have extended our earlier analysis[6] of the signals resulting from the decays $W\to\widetilde{W}\widetilde{Z}_{1,2}$ and $Z\to\widetilde{W}\overline{\widetilde{W}}$ or $\widetilde{Z}_2\widetilde{Z}_{1,2}$ at the CERN collider, where we had inferred the bound $m_{\widetilde{W}}\gtrsim 40$ GeV under the assumption that the lightest neutralino $\widetilde{Z}_1$ is dominantly a photino and $m_{\widetilde{Z}_1}<8$ GeV (i.e., $m_{\tilde{g}}\lesssim 53$ GeV). Our main results are summarized in Fig. 2. We see that the bound on the $\widetilde{W}$ mass that can be inferred from this analysis deviates considerably from the 40 GeV bound reported earlier when the model parameters are such that $\widetilde{Z}_1$ is no longer a photino. The main reason for this was traced to the increase in the mass of $m_{\widetilde{Z}_1}$, so that the p_T of the quarks from $\widetilde{W}$ and $\widetilde{Z}_2$ decay and also the $\not{p}_T$ become too soft to pass the UA1 cuts and trigger requirements. We have also noted that there are regions of the parameter space not excluded by this analysis but may be already excluded by the PETRA bound,[20] $m_{\widetilde{W}}>22$ GeV, or may soon be excluded at TRISTAN. Finally, we have remarked that the trilepton signatures discussed in Ref. 6 may be small in a large part of parameter space, but that the clean signatures from acollinear e^+e^-, $\mu^+\mu^-$, and $e^\mp\mu^\pm$ events from $\widetilde{W}$ pair production are still expected, although at a reduced rate.

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[9] In most cases, the heavier chargino and the other two neutralinos of the minimal model are too heavy to be produced via on-shell gauge-boson decays so that they will not affect our considerations. We have shown in Ref. 6 that nonresonant gaugino production is negligible.

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[14] The decays of Z to neutralinos were neglected in Ref. 6. For $\tilde{Z}_1 \approx \tilde{\gamma}$, the $Z\tilde{Z}_2\tilde{\gamma}$ coupling is forbidden by electromagnetic gauge invariance while the $Z\tilde{Z}_2\tilde{Z}_2$ coupling vanishes for the $v'/v=1$ case considered.

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[16] Because of cosmological considerations, the lightest SUSY particle is expected to be color and electrically neutral so that $m_{\tilde{W}} > m_{\tilde{Z}_1}$ is necessary except in models where $m_{\tilde{\nu}} < m_{\tilde{W}}$, for which the bound (3) applies.

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[19] In obtaining this limit we assumed that $m_{\tilde{Z}_1}=8$ GeV corresponding to $m_{\tilde{g}} \simeq 53$ GeV. The mass of $\tilde{Z}_2$ is fixed in terms of $m_{\tilde{W}}$ and $m_{\tilde{Z}_1}$ in the minimal model; $m_{\tilde{W}}=40$ GeV corresponds to $m_{\tilde{Z}_2} \simeq 45$ GeV in this region of parameter space.

[20] The $Z\tilde{Z}_1\tilde{Z}_2$ coupling vanishes for $v'/v=1$ unless one of $\tilde{Z}_1$ or $\tilde{Z}_2$ is the pure Higgsino state that is always present when $v'/v=1$. For all other cases this coupling is expected to be nonvanishing except for accidental cancellation. See, for example, Ref. 13.

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[22] Here, we have shown results only for the case $v'/v<1$ as is the case in supergravity models where the breakdown of SU(2)×U(1) is radiatively driven by top-quark Yukawa couplings (see Ref. 4). Since the masses of the gauginos are unaffected by the interchange, $v'/v \leftrightarrow v/v'$, the cut cross section for $v'/v>1$ can be obtained by simply scaling the gaugino production rates according to the formulas of Ref. 13.

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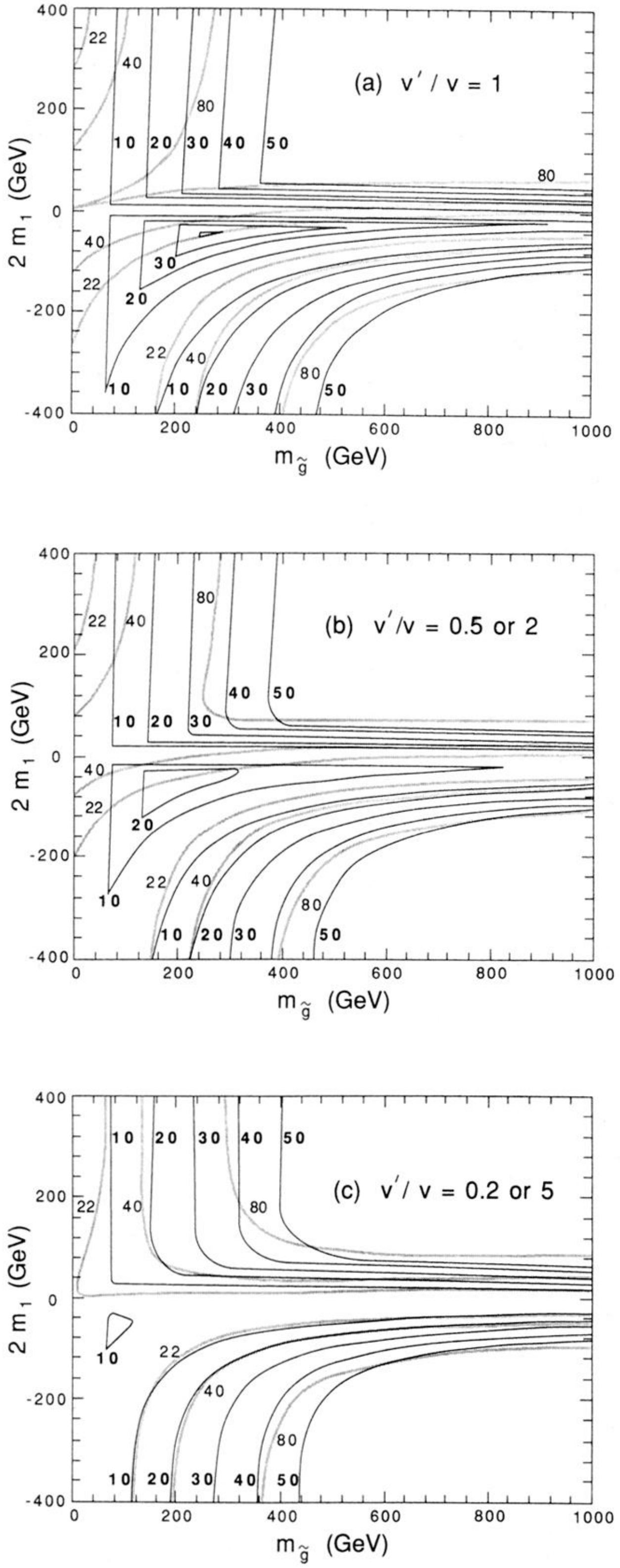

FIG. 1. A plot of the lightest neutralino ($\tilde{Z}_1$) and the lightest chargino ($\tilde{W}$) mass contours in the $m_{\tilde{g}}$ vs $2m_1$ (supersymmetric Higgsino mass) plane. We show contours for $m_{\tilde{W}}=22$, 40, 80 GeV by shaded lines and those for $m_{\tilde{Z}_1}=10$, 20, 30, 40, 50 GeV by solid lines. We show plots for (a) $v'/v=1$, (b) $v'/v=0.5$ or 2, and (c) $v'/v=0.2$ or 5, where v'/v is the ratio of the two Higgs-field vacuum expectation values.

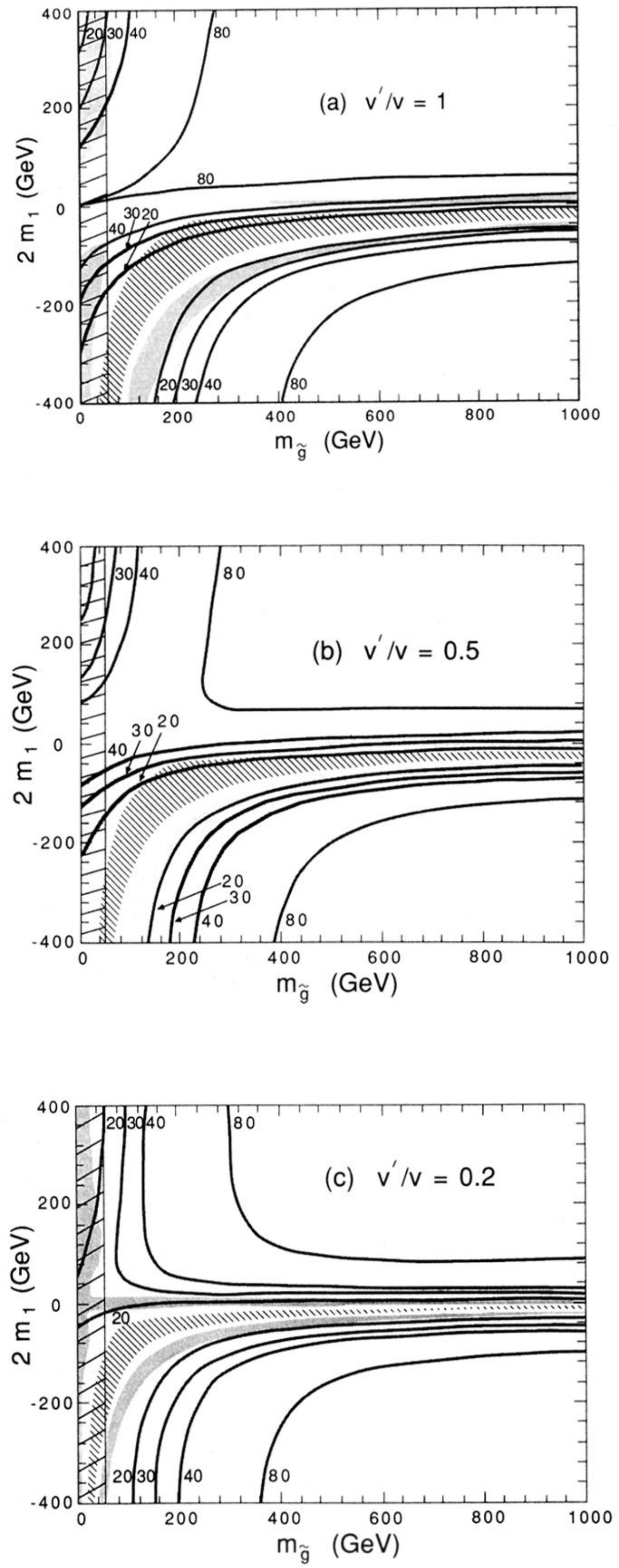

FIG. 2. A plot of excluded regions in the $m_{\tilde{g}}$ vs $2m_1$ plane for (a) $v'/v = 1$, (b) $v'/v = 0.5$, and (c) $v'/v = 0.2$. The region excluded by the present analysis is shown by the shaded area. Requiring $m_{\tilde{Z}_1} < m_{\tilde{W}}$ excludes the region shaded by diagonals. The UA1 bound $m_{\tilde{g}} > 53$ GeV is also shown. For reference, we show contours of $m_{\tilde{W}} = 20, 30, 40, 80$ GeV.