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Sparticle and Higgs-boson production and detection at CERN LEP II in two supergravity models

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We study the most promising signals for supersymmetry at CERN LEP II in the context of two well-motivated supergravity models: (i) the minimal SU(5) supergravity model including the stringent constraints from proton stability and a not too young universe and (ii) a recently proposed string-inspired no-scale flipped SU(5) supergravity model. Our computations span the neutralino, chargino, slepton, and Higgs sectors together with their interconnections in this class of models. We find that the number of "mixed" (1-lepton+2-jets+$\not{p}$) events occurring in the decay of pair-produced charginos ($\chi_1^{\pm}$) is quite significant (per $\mathcal{L}=100$ pb^{-1}) for both models and that these predictions do not overlap. That is, if $m_{\chi_1^{\pm}}<100$ GeV then LEP II should be able to exclude at least one of the two models. In the no-scale flipped SU(5) model we find that the number of acoplanar dielectron events from selectron pair production should allow for exploration of selectron masses up to the kinematical limit and chargino masses indirectly as high as 150 GeV. We find that the cross section $e^+e^-\to Z^*h$ deviates negligibly from the SM result in the minimal model, whereas it can be as much as $\frac{1}{3}$ lower in the flipped model. The usually neglected invisible mode $h\to\chi_1^0\chi_1^0$ can erode the preferred $h\to 2$ jets signal by as much as 40% in these models. We conclude that the charged slepton sector is a deeper probe than the chargino neutralino, or Higgs sectors of the flipped SU(5) model at LEP II, while the opposite is true for the minimal SU(5) model where the slepton sector is no probe at all.

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I. INTRODUCTION

The quest for a theoretical understanding of supersymmetry and its phenomenological consequences has been going on for over a decade. So far no supersymmetric particle has been directly observed in accelerator experiments or indirectly in proton decay or dark matter detectors. However, the recent precise measurements of the gauge coupling constants at the CERN e^+e^- collider LEP can be taken in the context of supersymmetric grand unification as indirect evidence for virtual supersymmetric corrections [1]. This observational situation may appear discouraging to some. However, it really should not since from a totally unbiased point of view, most sparticle masses could lie anywhere up to a few TeV, with no particular correlations among them. This means that existing facilities (Fermilab, LEP I,II, the DESY *ep* collider HERA, Gran Sasso) as well as future ones [CERN Large Hadron Collider (LHC), Superconducting Super Collider (SSC)] are needed in order to truly explore the bulk of the supersymmetric parameter space.

On the other hand, specific supergravity models incorporating well-motivated theoretical constraints can be very predictive, and perhaps even fully tested in the next few years with the present generation of collider experiments at Fermilab, HERA, and LEP II. We have recently focused our attention on two such models: (i) the minimal SU(5) supergravity model including the severe constraints of proton decay [2–6] and a not too young universe [4,6–8], and (ii) a recently proposed no-scale flipped SU(5) supergravity model [9]. The parameter spaces of these models have been scanned and a set of allowed points has been identified in each case. Several results then follow for the sparticle masses. These are summarized in Table I and discussed in detail in Refs. [4,6,7,10,11] for the minimal SU(5) model and in Refs. [9,10,11] for the flipped model. As far as the sparticle masses are concerned, perhaps the most striking difference between the two models is in the slepton masses which are below ≈ 300 GeV in the flipped SU(5) model, while they are out of reach of existing facilities, i.e., above 300 GeV, in the minimal SU(5) model. The study of the specific models such as the two we are pursuing singles out small regions of the vast 21-dimensional parameter space of the MSSM (minimal supersymmetric extension of the standard model). We have already shown [6,10] that experimental predictions for these models can be so precise that potential discovery or exclusion in the next few years is a definite challenge.

In a previous paper [10] we have studied the prospects for supersymmetry detection at Fermilab in the neutralino-chargino sector. Here we continue our general program by exploring the supersymmetric signals for charginos, neutralinos, sleptons, and the lightest Higgs boson at LEP II in the two models. For charginos we study the reaction $e^+e^-\to\chi_1^+\chi_1^-$ and the subsequent "mixed" (1 lepton plus 2 jets plus $\not{p}$) and dilepton decay signatures. We show that the predicted number of mixed events for both models are experimentally significant up to the kinematical limit, and do not overlap. Therefore, if

$m_{\chi_1^\pm} < 100$ GeV, then LEP II should be able to exclude at least one of the models. For neutralinos we analyze $e^+e^- \to \chi_1^0\chi_2$ and the dilepton signature, as a means to indirectly probe chargino masses above 100 GeV. The charged slepton sector appears very interesting for LEP II in the predictions of the flipped SU(5) supergravity model. We compute the number of dilepton events expected from pair-produced $\tilde{e}\tilde{e}$, $\tilde{\mu}\tilde{\mu}$, and $\tilde{\tau}\tilde{\tau}$, and conclude that these also should be accessible up to the kinematical limit. Finally, we explore the Higgs sector and study $e^+e^- \to Z^*h$ production, the branching ratios $h \to b\bar{b}$, $\tau^+\tau^-$, and $c\bar{c}, gg$ and the "invisible" mode $h \to \chi_1^0\chi_1^0$. We show that the latter can have a branching ratio as large as 30%, therefore significantly eroding the preferred $h \to 2$ jets mode. Nonetheless, detection is possible in a large fraction of parameter space for both models at LEP II. Throughout this paper we emphasize the interconnections among the various sectors of the models and their experimental consequences. For example, charged slepton pair production should indirectly probe chargino masses as high as 150 GeV in the flipped model.

II. CHARGINOS AND NEUTRALINOS

Among the various supersymmetric neutralino-chargino production processes accessible at LEP II, the one with the largest cross section is $e^+e^- \to \chi_1^+\chi_1^-$ which proceeds through s-channel γ^* and Z^* exchange and t-channel $\tilde{\nu}_L$ exchange. This cross section has been calculated in the literature [12–14] for various limiting cases of the chargino composition and for a general composition (i.e., an arbitrary linear combination of W-ino and charged Higgsino components) as well. We have independently calculated the cross section in the general case, and our result agrees with, e.g., Ref. [14]. The cross sections for this process for both models are shown in Fig. 1 for $\sqrt{s} = 200$ GeV. The reason the cross sections are lower in the no-scale flipped model is due to a well-known destructive interference between the s and t channels, which is relevant for light $\tilde{\nu}_L$ masses, or more properly for $m_{\tilde{\nu}_L} \sim m_{\chi_1^\pm}$. In addition, for $|\mu| \gg M_2 \approx 0.3 m_{\tilde{g}}$ [M_2 is the $SU(2)_L$ gaugino mass] the $\chi_1^\pm$ mass eigenstate is predominantly gaugino and therefore its coupling to lepton-slepton is not suppressed by the small lepton masses. In the minimal SU(5) the model, $m_{\tilde{\nu}_L} > 500$ GeV and the contribution of the t channel is small. In the flipped model $m_{\tilde{\nu}_L} \sim m_{\chi_1^\pm}$ and the destructive interference is manifest.

The best signature for this process is presumed to be the one-charged lepton ($e^\pm$ or $\mu^\pm$) + 2 jets $+\not{p}$ or "mixed" mode, where one chargino decays leptonically and the other one hadronically [15,16]. In the minimal SU(5), since the sleptons and squarks are heavy, the chargino decays are mediated dominantly by the W-exchange channels [10] and one gets

$$B(\chi_1^\pm \to \chi_1^0 l^\pm \nu_l)_{\text{minimal}} \approx \tfrac{2}{9} \quad (l = e + \mu)$$

and

$$B(\chi_1^\pm \to \chi_1^0 q\bar{q}')_{\text{minimal}} \approx \tfrac{2}{3} \ .$$

For the flipped case things are more complicated due to the light slepton-exchange channels. There are three regimes which one can identify: (i) when the slepton exchange channels dominate, the leptonic branching ratio (into $l = e + \mu$) is $\approx \frac{2}{3}$ and the hadronic one goes to zero; (ii) when the W-exchange channels dominate [as in the minimal SU(5) case], the leptonic branching ratio drops down to $\approx \frac{2}{9}$ and the hadronic one grows up to $\approx \frac{2}{3}$; and

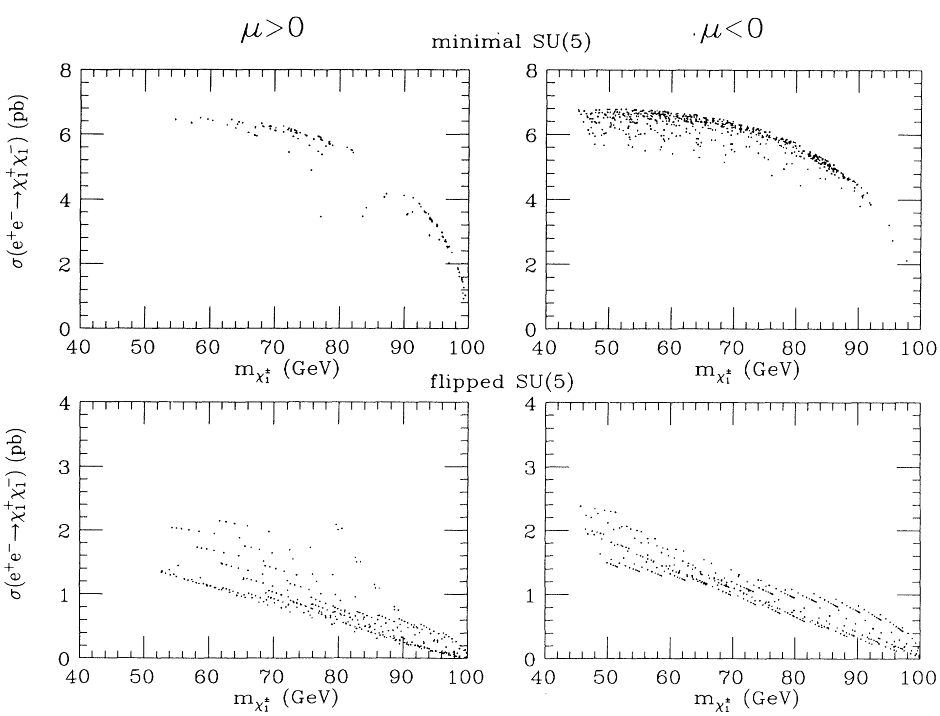

FIG. 1. The cross section for $e^+e^- \to \chi_1^+\chi_1^-$ at $\sqrt{s} = 200$ GeV as a function of chargino mass ($m_{\chi_1^\pm}$) for the minimal SU(5) supergravity model (top row) and the no-scale flipped SU(5) supergravity model (bottom row). The smaller size of the latter is due to destructive interference effects in the presence of a light sneutrino.

(iii) in the transition region between these two regimes, destructive interference between the W-exchange and slepton-exchange amplitudes can suppress the leptonic branching ratio and enhance the hadronic one beyond their values at the end of the transition. In Fig. 2 we show an example of this phenomenon for $m_t = 100$ GeV; for larger values of m_t the effect is less pronounced (see Fig. 2 in Ref. [10]).

In Fig. 3 we show the number of "mixed" events to be expected per $\mathcal{L} = 100\ \mathrm{pb}^{-1}$ for both models, i.e.,

$$\sigma(e^+e^- \to \chi_1^+\chi_1^-) B(\chi_1^+ \to \chi_1^0 l^+ \nu_l) B(\chi_1^\pm \to \chi_1^0 q\bar{q}') 2 ,$$

where the factor of 2 accounts for summing over the two charges of the outgoing lepton. The very small numbers for the flipped model which occur mostly for $\mu > 0$ correspond to points in the parameter space where the slepton-exchange channels dominate the chargino decays and the hadronic branching ratio goes to zero [case (i) in the previous paragraph]. Perhaps the most interesting feature of these results is that the predicted number of events for both models *do not overlap*. Therefore, *if* $m_{\chi_1^\pm} < 100$ GeV, then LEP II should be able to *exclude* at least one of the models (and possibly even both).

As far as the backgrounds are concerned, the dominant one is $e^+e^- \to W^+W^-$ with one W decaying leptonically and the other one hadronically. (To a lesser extent, the $f\bar{f}(\gamma)$, $Ze(e)$, $W\nu(e)$, ZZ, and $Z\nu\nu$ backgrounds also apply [17].) Several features of the chargino decays (such as an isolated lepton, missing mass, hadronic mass, etc.) allow for suitable cuts to be made which reduce the WW background to very small levels [16–18]. Model-dependent studies indicate that a 5σ effect (i.e., $S/\sqrt{B} \geq 5\sigma$) can be observed with $\mathcal{L} = 100$ (500) pb^{-1} of integrated luminosity for

$$\sigma(e^+e^- \to \chi_1^+\chi_1^-) \gtrsim 0.40\ (0.17)\ \mathrm{pb}$$

(Ref. [18]). These calculations assume W-exchange dominance in chargino decays [case (ii) above] and are therefore applicable to the minimal SU(5) model. In this case Fig. 3 shows that one could explore all allowed points in parameter space with $m_{\chi_1^\pm} < 100$ GeV, since $\sigma \gtrsim 0.40$ (0.17) pb for $\mathcal{L} = 100$ (500) pb^{-1} would require 40 (85) observed events. Moreover, since in this model $m_{\chi_1^\pm} < 104$ (92) GeV for $\mu > 0$ ($\mu < 0$) [11], only a few points in parameter space should remain unexplored in this direct way at LEP II.

For the flipped model the experimental study referred to above may not apply since the W-exchange dominance assumption is not likely to hold for $m_{\chi_1^\pm} < 100$ GeV (see, e.g., Fig. 2). Assuming that the results apply at least approximately, we can see that a fraction of the parameter space for $m_{\chi_1^\pm} < 100$ GeV could be explored. If no signal is observed, this would imply that $m_{\chi_1^\pm} > 100$ GeV in the minimal SU(5) model, but not necessarily in the flipped model because of possible highly suppressed hadronic decay channels. To probe the remaining unexplored regions of the flipped model for $m_{\chi_1^\pm} < 100$ GeV we show in Fig. 4 the predicted number of events for $e^+e^- \to \chi_1^+\chi_1^- \to$ dileptons which does not suffer from small chargino hadronic branching ratios. However, the efficiency cut needed to suppress the backgrounds to this process is not known at present. Nevertheless, the signal is significant and should encourage experimental scrutiny.[1] For the minimal SU(5) case the dilepton signal is $\frac{1}{6}$

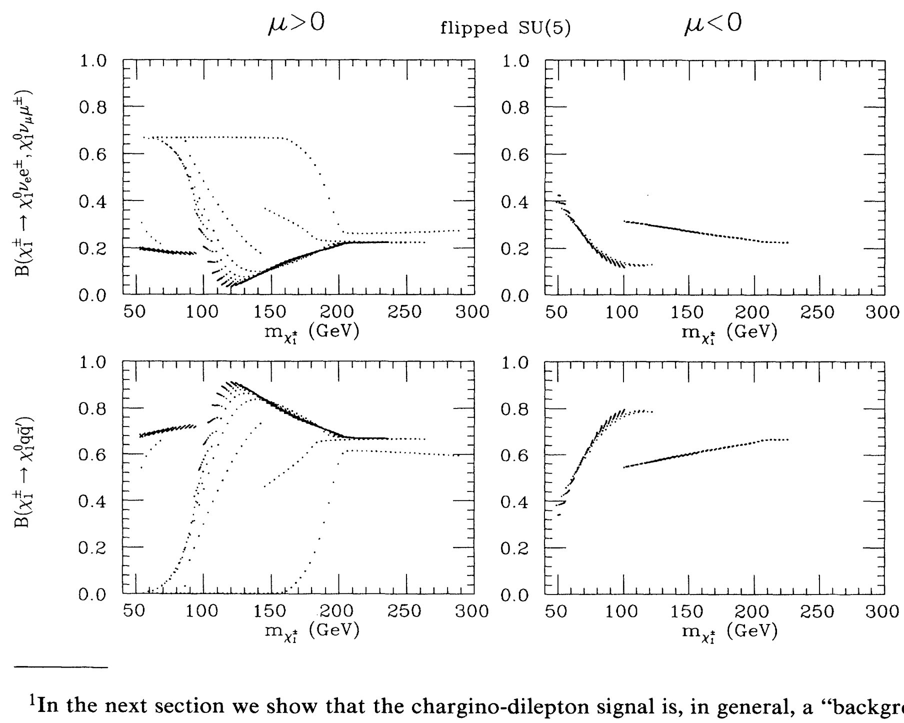

FIG. 2. The leptonic and hadronic branching ratios for the chargino in the flipped model and $m_t = 100$ GeV. The former ranges from $\approx \frac{2}{3}$ when the slepton-exchange channels dominate, down to $\approx \frac{2}{9}$ when the W-exchange channels dominate, and through very small values when the two channels interfere destructively. A complementary effect is seen to happen for the hadronic branching ratio.

[1]In the next section we show that the chargino-dilepton signal is, in general, a "background" to dileptons from charged slepton decays. Therefore experimental isolation of the chargino-dilepton signal may be required anyway.

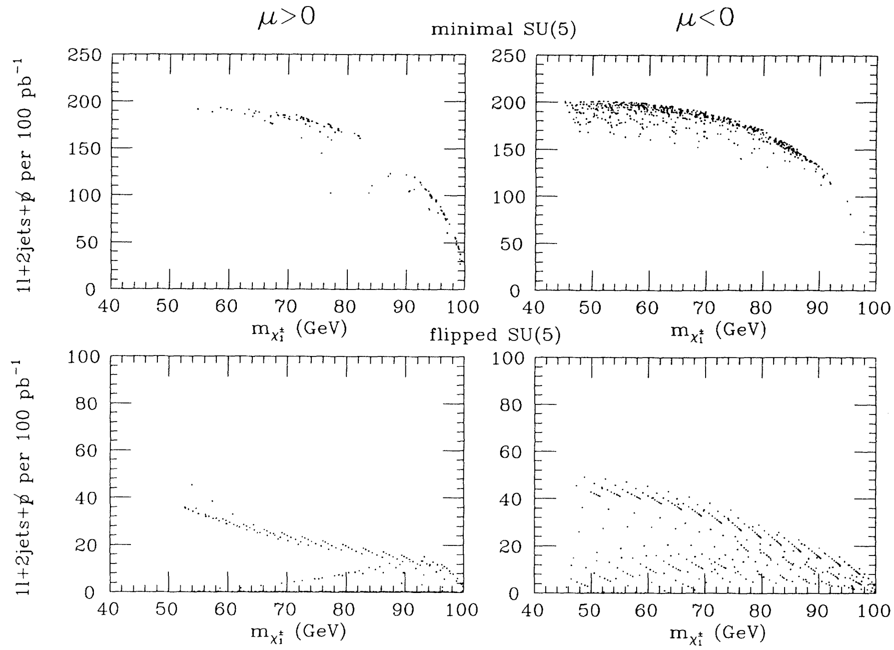

FIG. 3. The number of "mixed" (1 lepton +2 jets + $\not{p}$) events per $\mathcal{L}=100$ pb^{-1} for both models. Note that the predictions on the top row *do not overlap* with those on the bottom one, and therefore if $m_{\chi_1^\pm}<100$ GeV, LEP II should be able to exclude at least one of the models.

of that for the mixed mode: a factor of 3 is lost in substituting the hadronic branching fraction ($\frac{2}{3}$) for the leptonic one ($\frac{2}{9}$), and a further factor of 2 from not needing to sum over the charges of the outgoing lepton. Thus, Fig. 3 (top row $\times\frac{1}{6}$) shows that the minimal model dilepton signal is generally smaller than the flipped model one.

Concerning neutralino detection at LEP II [12,19], the largest observable cross section occurs for $e^+e^-\to\chi_1^0\chi_2^0$ which is mediated by Z^* s-channel exchange and $\tilde{e}_{L,R}$ t-channel exchange. Since in the models we consider $m_{\chi_1^\pm}\approx m_{\chi_2^0}\approx 2m_{\chi_1^0}$, this process could explore indirectly chargino masses up to ~ 130 GeV and may be worth considering despite the potentially small rates. The coupling $Z\chi_1^0\chi_2^0$ depends exclusively on the Higgsino admixture of χ_1^0 and χ_2^0 and is thus highly suppressed here (and so is the s-channel amplitude) and in any model where $|\mu|\gg M_2$. The cross section then depends crucially on the t-channel amplitude, i.e., on the selectron mass. For the minimal SU(5) model we find

$$\sigma(e^+e^-\to\chi_1^0\chi_2^0)<10\text{ fb}$$

since $m_{\tilde{e}_{L,R}}>500$ GeV. Even with 100% efficiencies and high branching ratios, it would take at least $\mathcal{L}=1000$ pb^{-1} to get an observable signal at the largest cross section. For $m_{\chi_1^\pm}>100$ GeV the cross section drops below 0.1 fb and therefore this mode is hopeless for exploration of chargino masses above 100 GeV at LEP II in the minimal SU(5) model.

For the flipped model we have $m_{\tilde{e}_R}<190$ GeV and $m_{\tilde{e}_L}<300$ GeV and thus the cross section for $e^+e^-\to\chi_1^0\chi_2^0$ is correspondingly much larger, although slightly below 1 pb at most; see Fig. 5 top row. With $\mathcal{L}=500$ pb^{-1} and a neutralino dilepton branching ratio as high as $\frac{2}{3}$ (see Fig. 4 in Ref. [10]), one could get an observable number of neutralino-dilepton ($\chi_2^0\to\chi_1^0 l^+l^-$) events even for $m_{\chi_1^\pm}>100$ GeV; see Fig. 5 bottom row.[2]

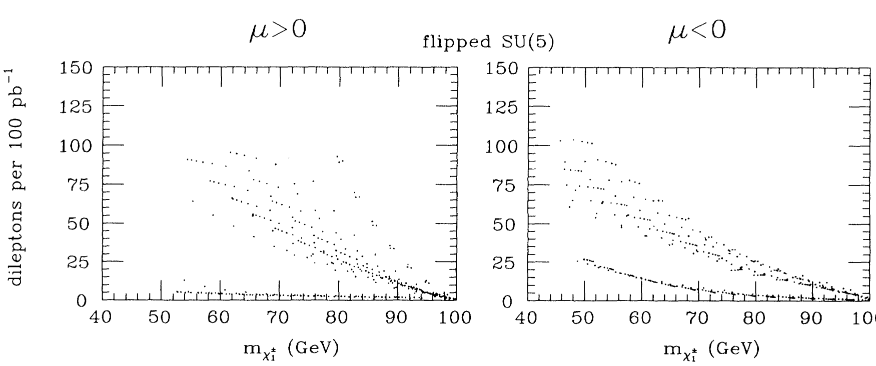

FIG. 4. The number of dilepton events per $\mathcal{L}=100$ pb^{-1} to be expected from the process $e^+e^-\to\chi_1^+\chi_1^-$ for the flipped model. The corresponding number in the minimal SU(5) model is $\frac{1}{6}$ of that shown on the top row in Fig. 3.

[2]Note that neutralino dileptons need still to be distinguished from the chargino dileptons discussed above; the one-sided nature of the former signal may help in this regard.

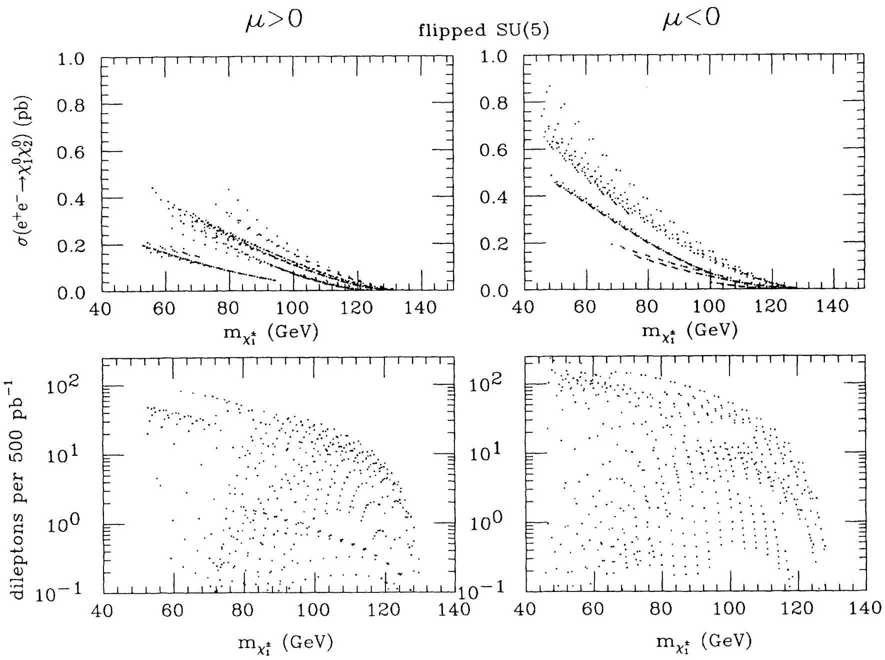

FIG. 5. The cross section for $e^+e^-\to\chi_1^0\chi_2^0$ for the flipped model as a function of the chargino mass. Note that chargino masses up to ≈ 130 GeV could be explored with this process. Also shown is the number of dilepton events per $\mathcal{L}=500$ pb^{-1}.

Most of the backgrounds to this process can be reduced, except for the *WW* one which was shown in Ref. [16] to overwhelm the signal for both leptonic and hadronic decays, at least for the parameters considered by those authors. A reevaluation of this analysis in the light of the flipped model cross section and branching ratios would need to be performed to be certain of the fate of this mode. Since this is one way in which LEP II could indirectly explore chargino masses above 100 GeV, it would appear to be a worthy exercise.

III. SLEPTONS

The charged sleptons ($\tilde{e}_{L,R},\tilde{\mu}_{L,R},\tilde{\tau}_{L,R}$) offer an interesting supersymmetric signal through the dilepton decay mode, if light enough to be produced at LEP II [12,15,16,20,21]. This is partially the case for the flipped SU(5) model where $m_{\tilde{e}_L}\lesssim 300$ GeV and $m_{\tilde{e}_R}\lesssim 200$ GeV. [No such signal exists at LEP II for the minimal SU(5) model since $m_{\tilde{l}}>300$ GeV.] We have computed the cross sections for

$$e^+e^-\to\tilde{e}_L^+\tilde{e}_L^-,\tilde{e}_R^+\tilde{e}_R^-,\tilde{e}_L^\pm\tilde{e}_R^\mp\ , \tag{3.1a}$$

$$e^+e^-\to\tilde{\mu}_L^+\tilde{\mu}_L^-,\tilde{\mu}_R^+\tilde{\mu}_R^-\ , \tag{3.1b}$$

$$e^+e^-\to\tilde{\tau}_L^+\tilde{\tau}_L^-,\tilde{\tau}_R^+\tilde{\tau}_R^-\ . \tag{3.1c}$$

The $\tilde{e}_L^+\tilde{e}_L^-,\tilde{e}_R^+\tilde{e}_R^-$ final states receive contributions from *s*-channel γ^* and Z^* exchanges and *t*-channel χ_i^0 exchanges, while the $\tilde{e}_L^\pm\tilde{e}_R^\mp$ only proceeds through the *t* channel. The $\tilde{\mu}_L^+\tilde{\mu}_L^-,\tilde{\mu}_R^+\tilde{\mu}_R^-$ and $\tilde{\tau}_L^+\tilde{\tau}_L^-,\tilde{\tau}_R^+\tilde{\tau}_R^-$ final states receive only *s*-channel contributions, since all couplings are lepton flavor conserving, and therefore mixed *LR* final states are not allowed for smuon or stau production. Our results agree with those in Ref. [21]. Note that in the flipped model the left-handed (L) slepton masses are considerably heavier than the right-handed (R) ones (see Fig. 3 in Ref. [9]). In particular,

$$m_{\tilde{\tau}_R}<m_{\tilde{e}_R,\tilde{\mu}_R}<m_{\tilde{e}_L,\mu_L}<m_{\tilde{\tau}_L}\ .$$

The acoplanar dilepton signal associated with selectron pair production has been traditionally assumed to come entirely from $\tilde{e}_{L,R}^\pm\to e^\pm\chi_1^0$ decay channels, i.e., purely dielectrons. This is an idealization which need not hold in specific supergravity models. In the flipped model the following decay channels are allowed:

$$\tilde{e}_L^\pm\to e^\pm\chi_1^0,e^\pm\chi_2^0,\nu_e\chi_1^\pm\ , \tag{3.2a}$$

$$\tilde{e}_R^\pm\to e^\pm\chi_1^0,e^\pm\chi_2^0\ . \tag{3.2b}$$

If χ_2^0 decays invisibly ($\chi_2^0\to\nu\bar{\nu}\chi_1^0$) and $\chi_1^\pm$ leptonically ($\chi_1^\pm\to l^\pm\nu_l\chi_1^0, l=e,\mu,\tau$), then one has new contributions to the sought-for dilepton signal. Note however that in the latter case the charged leptons (e,μ,τ) will be "nonleading" and thus their spectrum (from three-body $\chi_1^\pm$ decay) is likely to deviate from the "leading" lepton spectrum (from two-body $\tilde{e}_{L,R}$ decay). Because of the details of the model, more than 90% of the points in the allowed parameter space have $m_{\tilde{e}_R}<m_{\chi_2^0}$ and therefore $B(\tilde{e}_R^\pm\to e^\pm\chi_1^0)=100\%$ for these points; the remaining points, which allow $m_{\tilde{e}_R}>m_{\chi_2^0}$, have branching fractions to $e^\pm\chi_1^0$ no smaller than 75%. On the other hand, for all points in parameter space we find $m_{\tilde{e}_L}>m_{\chi_2^0,\chi_1^\pm}$ and the decays of the heavier $\tilde{e}_L$ proceed in all three ways.

It is important to realize that in this model, for a given point in parameter space, all slepton masses are determined, and the lighter of the final states in Eq. (3.1a) ($\tilde{e}_R^+\tilde{e}_R^-$) will dominate the total cross section into selectron pairs. Moreover, the dilepton signal from this dominant contribution will be purely leading dielectrons. The other final states in Eq. (3.1a) involving the heavier $\tilde{e}_L(\tilde{e}_L^{\pm}\tilde{e}_R^{\mp},\tilde{e}_L^{+}\tilde{e}_L^{-})$ have smaller cross sections and contribute mostly leading dielectrons. This is because nonleading leptons (e,μ,τ) require the production of the heavier $\tilde{e}_L^{\pm}$ and the further branching ratio suppressed decay into $\nu_l\chi_1^{\pm}$. Therefore, we expect the traditional acoplanar dielectron $+\not{p}$ (missing energy) signature to prevail.

We have computed the total (leading) dielectron signal (per $\mathcal{L}=100$ pb^{-1}) from all channels in Eq. (3.1a). The result is shown in Fig. 6 (top row) as a function of the selectron mass $m_{\tilde{e}_R}$. The thinning of the point distributions for $m_{\tilde{e}_R}\gtrsim 80$ GeV is due to the kinematical closing of the $\tilde{e}_L^{\pm}\tilde{e}_R^{\mp}$ production channel. The number of dielectron events is quite significant and with adequate experimental efficiencies to account for the dielectron WW,ZZ decay backgrounds [17,18,22] it should be possible to explore the whole kinematical allowed mass range (i.e., $m_{\tilde{e}_R}\lesssim 100$ GeV and indirectly larger $m_{\tilde{e}_L}$ masses) with $\mathcal{L}=500$ pb^{-1}. For example, a study in Ref. [17] indicates that one would need $\sigma(e^+e^-\to\tilde{e}\tilde{e})\gtrsim 0.1$ pb to observe a 5σ effect. From Fig. 6 this will allow exploration up to $m_{\tilde{e}_R}\approx 95$ GeV.

The analysis in the previous paragraphs for selectron pair production can be carried over to $\tilde{\mu}$ and $\tilde{\tau}$ pair production. In this case $\tilde{\mu}_R^+\tilde{\mu}_R^-$ and $\tilde{\tau}_R^+\tilde{\tau}_R^-$ dominate the production cross section and the leading dimuons and di-τ's constitute the bulk of the dilepton signal, respectively. Furthermore, nonleading leptons (e,μ,τ) are even less likely to occur here since the larger contributions from LR final states (compared to LL final states) in the selectron case are not present here. In Fig. 6 (bottom row) we show the result for the di-τ case; the dimuon signal is very similar. These signals are smaller (although not by too much) than the dielectron signal in selectron pair production because of the fewer production diagrams.

The slepton dilepton signal could also be used to explore indirectly values of the chargino masses beyond the direct kinematical limit of 100 GeV. In Fig. 7 (top row) we show the $\tilde{e}$ dielectron signal versus the chargino mass, and observe that, in principle, one could probe as high as $m_{\chi_1^{\pm}}\approx 150$ GeV. In fact, this indirect method appears to be much more promising than the one suggested in Sec. II through the $\chi_1^0\chi_2^0$ channel.

It is important to realize that dileptons also occur in chargino (and to a lesser extent χ_2^0) decays, as discussed for the flipped model in Sec. II. In Fig. 7 (bottom row) we show the number of chargino-dileptons from Fig. 4 but this time plotted against $m_{\tilde{e}_R}$. This "background" to slepton-dileptons (the search topology for dileptons is the same) has some features which may allow for it to be sufficiently accounted for. The slepton-dileptons contain only (leading) l^+l^- $(l=e,\mu$ for now) pairs, whereas the chargino-dileptons in Fig. 7 contain a mixture of 25% e^+e^-, 25% $\mu^+\mu^-$, and 50% $e^{\pm}\mu^{\mp}$. Moreover, the common l^+l^- pairs have a different energy spectrum (c.f. $\tilde{l}^{\pm}\to l^{\pm}\chi_1^0$ with $\chi_1^{\pm}\to l^{\pm}\nu_l\chi_1^0$). Of course, if charginos are observed through the mixed signal, one could simply "subtract out" the ensuing chargino dilepton signal from the total observed (chargino + slepton) dilepton signal.

The previous two paragraphs exemplify the interconnections among the various sectors of this class of models. These correlations allow experimental exploration of one sector to probe indirectly other sectors. They also allow for a reliable computation of all contributing sectors to a particular physics signal (such as acoplanar dielectrons).

We have not considered the production of sneutrinos since because of their masses (in between the R and L charged lepton masses) the rates will be lower than for selectron production. Moreover, their visible decay

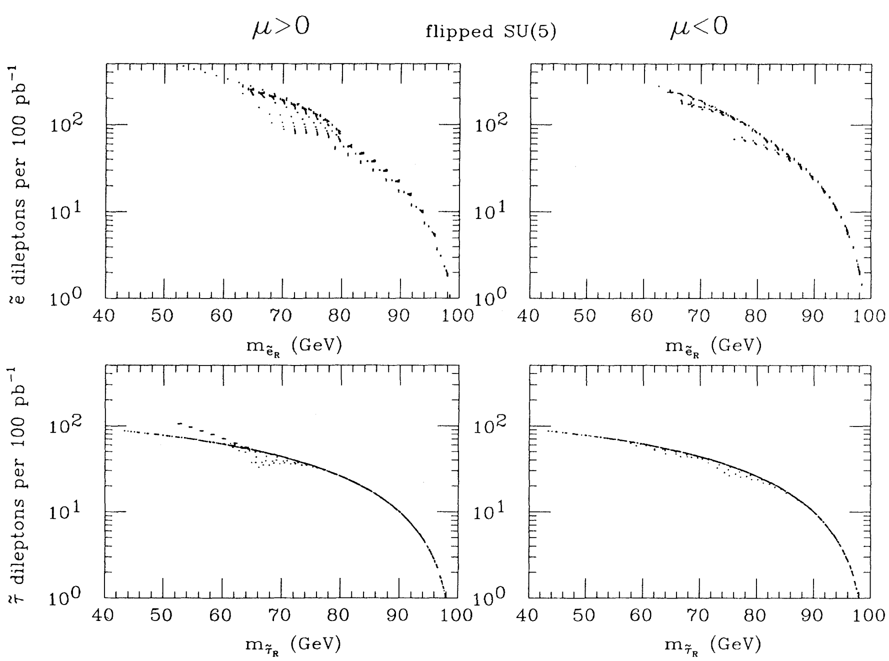

FIG. 6. The number of dielectron events per $\mathcal{L}=100$ pb^{-1} from selectron pair production (top row) and the corresponding number of di-τ's from stau pair production (bottom row), as a function of the lightest charged slepton mass of the corresponding flavor. The results for the dimuons from smuon pair production are very similar to the number of di-τ's.

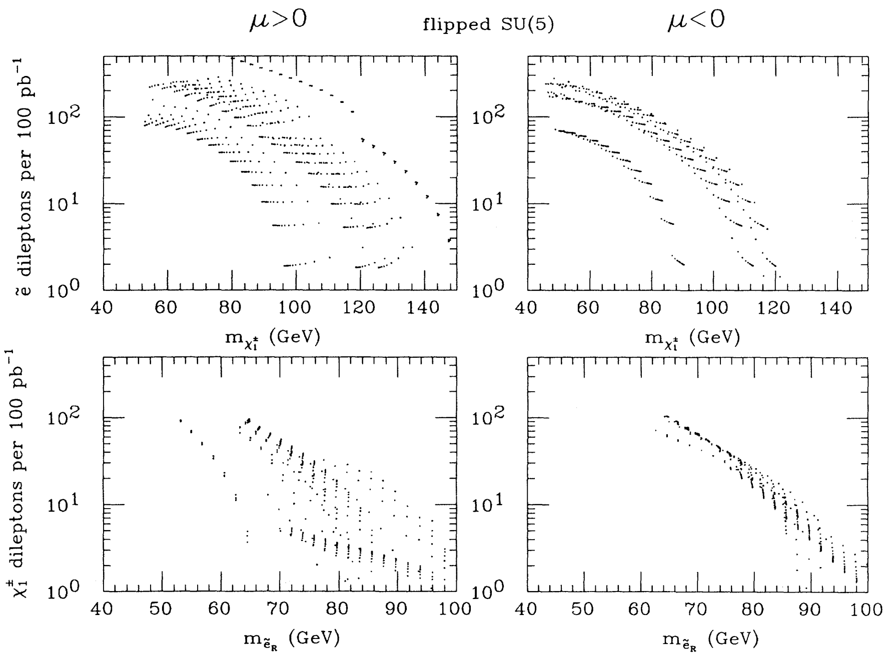

FIG. 7. The number of dielectrons from selectron pair production as in Fig. 6, but plotted against the chargino mass (top row), showing that one could indirectly probe chargino masses as high as 150 GeV. Also shown (bottom row) are the chargino dileptons from Fig. 4 which are comprised of 25%, 25%, and 50% of ee, $\mu\mu$, and $e\mu$ dileptons, respectively.

channels ($\tilde{\nu}_e \to \nu_e \chi_2^0, e^{\pm}\chi_1^{\mp}$) are branching-ratio suppressed (since $\tilde{\nu}_e \to \nu_e \chi_1^0$ is expected to dominate), and will lead to one-sided (likely soft) dileptons.

IV. THE LIGHTEST HIGGS BOSON

We now consider the standard alternative to direct sparticle production and decay modes, namely, the SUSY Higgs sector. Since the supergravity models we consider here contain two complex Higgs doublets, after spontaneous symmetry breaking the physical Higgs spectrum contains the usual h,H (CP even) and A (CP odd) neutral Higgs fields, and the charged $H^{\pm}$ Higgs field. For a comprehensive review of the SUSY Higgs sector, we refer the reader to Ref. [23]. Our goal in this section is to reformulate the "generic" analysis for SUSY Higgs-boson production and decay in terms of the *specific* minimal and flipped SU(5) supergravity models described above. As a result we must include some nonstandard decay channels, such as $h \to \chi_1^0\chi_1^0$, which are usually not considered in generic analyses since they are so model dependent. Significantly, $B(h \to \chi_1^0\chi_1^0)$ can be quite large in these models, and this modifies the usual assumptions regarding Higgs signals at colliders. We also incorporate the one-loop corrections to the Higgs-boson masses which can be quite significant in large regions of parameter space [24].

From the underlying radiative breaking mechanism in the two supergravity models we consider [25], and the experimental lower bound on the gluino mass, one can show [11] that the Higgs sector of both models approaches a SM-like situation with a light scalar (h) with SM-like couplings, and a heavy Higgs spectrum ($H, A, H^{\pm}$) which tends to decouple from fermions and gauge bosons for increasing $m_{\tilde{g}}$ (see Ref. [11] for further details). The approach to this limit is accelerated (as a function of $m_{\tilde{g}}$) in the minimal SU(5) model due to the proton decay constraint which requires large scalar masses. In the flipped model the A Higgs boson can be relatively light for large $\tan\beta (m_A \gtrsim m_h)$, implying a slower approach to the limiting situation. For the most part then, we need only consider the h Higgs boson at LEP. Thus, the phenomenological analysis of the Higgs sector for each supergravity model simplifies dramatically, particularly when making contact with previous experimental and Monte Carlo results. With proper care for the nonstandard hZZ coupling and branching ratios (which simply amounts to a rescaling of the SM analysis), we can adopt the definitive SM analysis of Ref. [26] for $m_{H_{SM}} \lesssim 80$ GeV along with the recent results summarized in Ref. [22] for $m_{H_{SM}} \gtrsim 80$ GeV.

With regard to Higgs-boson production, since we take $\sqrt{s} = 200$ GeV, the only relevant mode is the standard s-channel $e^+e^- \to Z^*h \to hf\bar{f}$ production process, since the $Hf\bar{f}$, H^+H^- final states are kinematically forbidden, and the WW-fusion t-channel processes are relevant only for $\sqrt{s} \gtrsim 400$ GeV $+0.6 m_h$ [23]. For the flipped case, there are a few exceptional ($<1\%$) points in the allowed parameter space for which the associated $e^+e^- \to hA$ process is kinematically allowed (i.e., for $m_h \lesssim m_A \lesssim 90$ GeV which is possible for large $\tan\beta$ values, see Fig. 6 in Ref. [9]); we neglect this mode in our analysis. In Fig. 8 we show the cross section $\sigma(e^+e^- \to Z^*h \to h\nu\bar{\nu})$ vs m_h for both models for $\sqrt{s} = 200$ GeV. The values shown for the minimal SU(5) model also correspond to the SM result since one can verify

$$\frac{\sigma(e^+e^- \to Z^*h)}{\sigma(e^+e^- \to Z^*H_{SM})} = \sin^2(\alpha - \beta) > 0.9999$$

in this case [11]. As a reference point, for $m_h = 80$ GeV, and the canonical integrated luminosity of 500 pb^{-1}, the

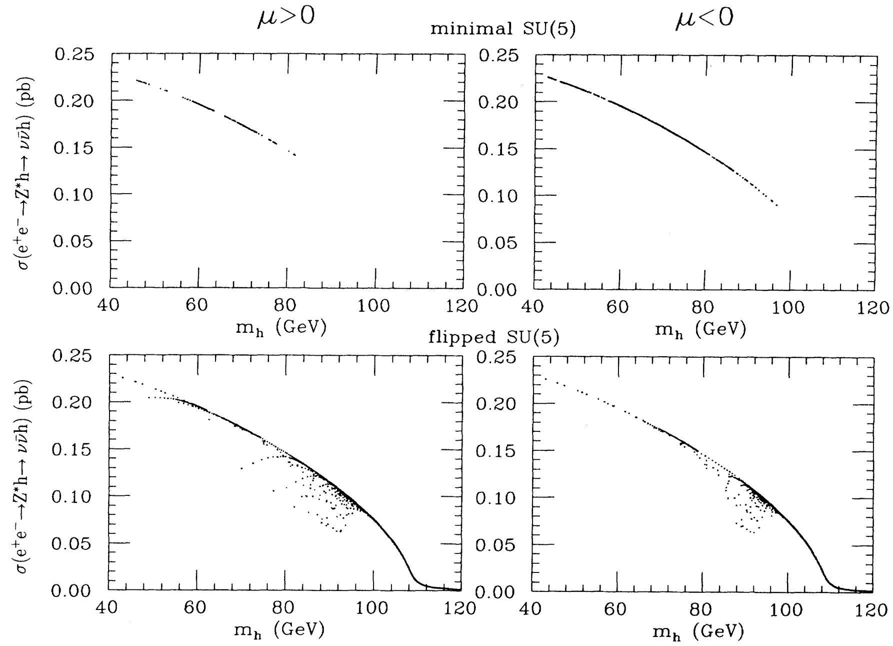

FIG. 8. The cross section at $\sqrt{s}=200$ GeV for $e^+e^- \to Z^*h \to h\nu\bar{\nu}$ for the minimal SU(5) model (top row) and the flipped model (bottom row) as a function of the Higgs mass m_h. In the minimal SU(5) model the cross section differs negligibly from the SM result, whereas in the flipped model decreases of up to $\approx\frac{1}{3}$ are possible for a small ($<1\%$) set of points in the allowed parameter space corresponding to relatively light values of m_A. Note the "tail" in the cross section in the flipped case for $m_h \gtrsim 110$ GeV when the second Z goes off shell.

SM [and also the minimal SU(5)] value of $\sigma \simeq 0.145$ pb would correspond to approximately 62 $b\bar{b}\nu\bar{\nu}$ events (56 if initial state radiation is included) [26]. The "tail" in the cross section when the second Z is forced off shell is evident in the flipped case for $m_h \gtrsim 110$ GeV. In this model, significant deviations from the SM curve are possible (see Fig. 8 and compare top and bottom rows), and these correspond to the small set of points ($<1\%$) for which m_A can achieve moderately light values ($m_A \gtrsim m_h$ for large $\tan\beta$). Since in this case $\sin(\alpha-\beta) \gtrsim 0.8$, a reduction of up to $\approx\frac{1}{3}$ in the cross section is possible compared to the SM case. We should add that these results agree quite well with previous results obtained in Ref. [27] for a slightly different version of the no-scale flipped SU(5) supergravity model. There the reduction in $\sin^2(\alpha-\beta) \sim 0.8$ is only possible for large $\tan\beta$ values, and 80 GeV $\lesssim m_h \lesssim 100$ GeV. In addition, in Ref. [27] it was found that $m_h \lesssim 120$ GeV, and this limit is close to the one obtained in the present version of the flipped model ($m_h \lesssim 135$ GeV).

Regarding the decay of the h Higgs boson, it is well known that higher-order QCD corrections can be important and affect the overall results for the relevant decay channels $h \to b\bar{b}, c\bar{c}$ by up to 20% [28]. This should be particularly true at LEP II, where m_h is much greater than $m_{c,b}$ and there will be significant running of the quark masses from the scale $Q=m_{c,b}$ up to $Q=m_h$. We therefore choose to include QCD corrections to $O(\alpha_s^2)$ as outlined in detail in Ref. [29]. In addition, significant departures from the usual SM branching ratios result when we include the $h \to \chi_1^0\chi_1^0$ decay channel. Statistically speaking, we find that 7% (12%) of the points for the flipped model for $\mu>0$ ($\mu<0$) kinematically allow for this nonstandard decay mode. In the minimal SU(5) case, this fraction rises to 26% (36%) for $\mu>0$ ($\mu<0$).[3] In Figs. 9 and 10 we show the branching ratios for $h \to b\bar{b}$, and $\chi_1^0\chi_1^0$, respectively, for both models. For $B(h \to b\bar{b})$, the "standard" expectation of ≈ 0.85 is evident; however, the value can be reduced down to 0.6 (0.5) in the minimal (flipped) SU(5) model predominantly due to the opening of the $\chi_1^0\chi_1^0$ channel. (The few points for $\mu<0$ in the minimal model which have yet smaller branching ratios correspond to an enhancement of the $h \to gg$ rate, as described below.) In the flipped case, the $h \to \chi_1^0\chi_1^0$ mode is maximized for $m_h \approx 105$ GeV (see Fig. 10 bottom row), while for the minimal case this happens for $m_h \gtrsim 75$ GeV (see Fig. 10 top row).

As for the other decay channels ($h \to gg, \tau^+\tau^-, c\bar{c}$), in Fig. 11 we show the $B(h \to gg)$, which varies considerably over the parameter space, and generally increases with m_t.[4] The three packs of curves in Fig. 11 for the flipped model (bottom row) correspond from left to right to $m_t=100$, 130, 160 GeV; the further structure is due to the $\tan\beta$ values used which increment in steps of two units starting at $\tan\beta=2$ and accumulate for large $\tan\beta$. For the flipped model we find $B(h \to gg) \lesssim 0.2$. This is generally true for the minimal model also, except for some extreme cases for large $m_t \simeq 160$ GeV, when it can be as large as ≈ 0.9. This enhancement is due to a large $\tilde{t}_{L,R}$ mixing (which occurs in a small region of parameter space), which results in a *very* light stop mass $m_{\tilde{t}_1} \approx 50$

[3]There are only a handful of points for which the $h \to \chi_1^0\chi_2^0$ mode is kinematically accessible in the flipped model [there are none in the minimal SU(5) model] with $B(h \to \chi_1^0\chi_2^0) \lesssim 10^{-4}$. We do not show these points here.

[4]We use the expressions for $h \to gg$ that appear in Ref. [30] along with minor corrections pointed out by those authors.

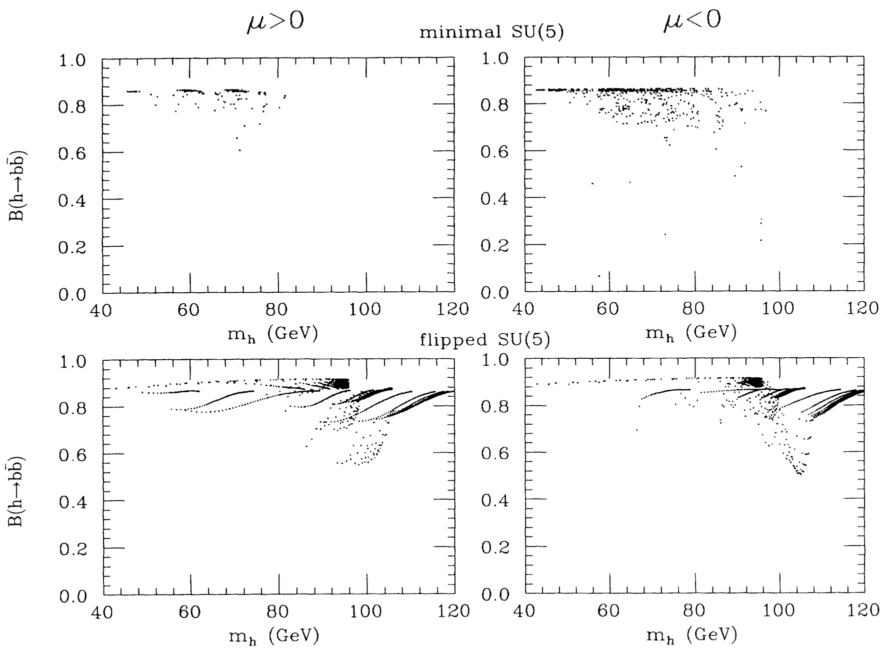

FIG. 9. The branching ratio for $h \to b\bar{b}$ as a function of the Higgs-boson mass m_h for the minimal SU(5) model (top row), and the flipped model (bottom row). Note the significant departures from the SM result ($\approx 85\%$) due to the opening of the $h \to \chi_1^0\chi_1^0$ (and to a lesser extent the $h \to gg$) channel.

GeV and therefore suppresses the $b\bar{b}$ mode significantly [note the points with uncharacteristically small values of $B(h \to b\bar{b})$ in Fig. 9, top row, for $\mu < 0$]. We expect $B(h \to \gamma\gamma)$ to be much smaller, and do not include this mode in our analysis here.

Although not shown, we have calculated $B(h \to \tau^+\tau^-)$ also, and find that for both models, this channel is confined to a narrow band centered around $B(h \to \tau^+\tau^-) = 0.08$; this agrees well with the results obtained in Refs. [29,31]. In Fig. 12 we show $B(h \to c\bar{c})$ for both models. For the flipped case, there is a large range of values $[0.0001 \lesssim B(h \to c\bar{c}) \lesssim 0.06]$, with a noticeable dip in the range 80 GeV $\lesssim m_h \lesssim$ 100 GeV corresponding to the deviation from the SM couplings. For the minimal SU(5) case, $B(h \to c\bar{c}) \sim 0.06$. The latter result is predominantly due to the fact that in the minimal case $\sin(\alpha - \beta) \approx 1$ and therefore the h-c-$\bar{c}$ coupling ($\propto \cos\alpha / \sin\beta$) goes to the SM H_{SM}-c-$\bar{c}$ coupling, for virtually all points.

Detectability of the h Higgs boson requires the combination of production and experimentally important decay modes, as well as a detailed treatment of the backgrounds and overall efficiency.[5] From our previous discussion of h production and decay, it is clear that the

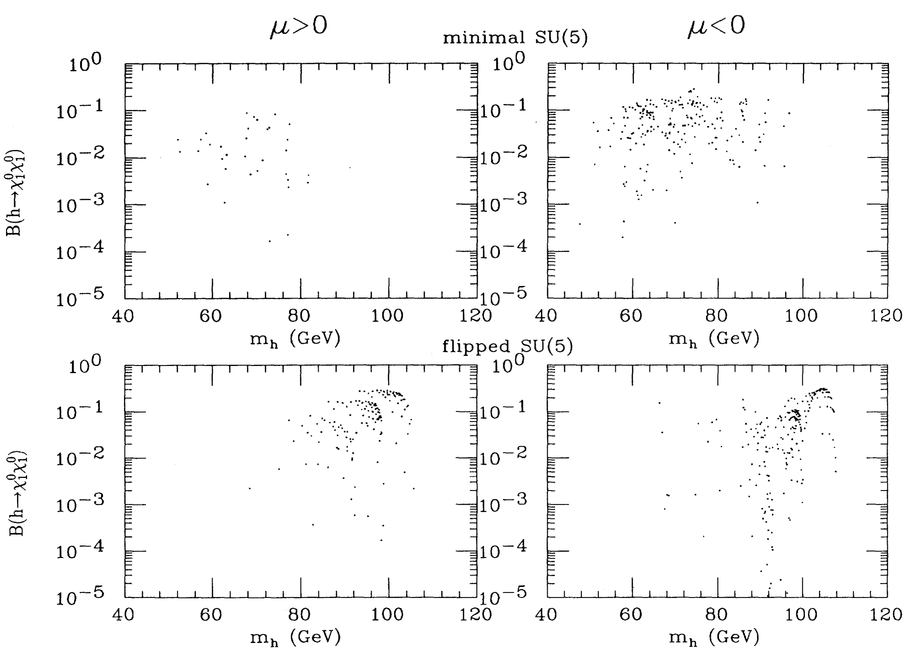

FIG. 10. The branching ratio for $h \to \chi_1^0\chi_1^0$ as a function of the Higgs-boson mass m_h for the minimal SU(5) model (top row) and the flipped model (bottom row).

[5]In what follows we adapt the results of Ref. [26] for the SM Higgs boson to the h Higgs boson for $m_h \lesssim 80$ GeV.

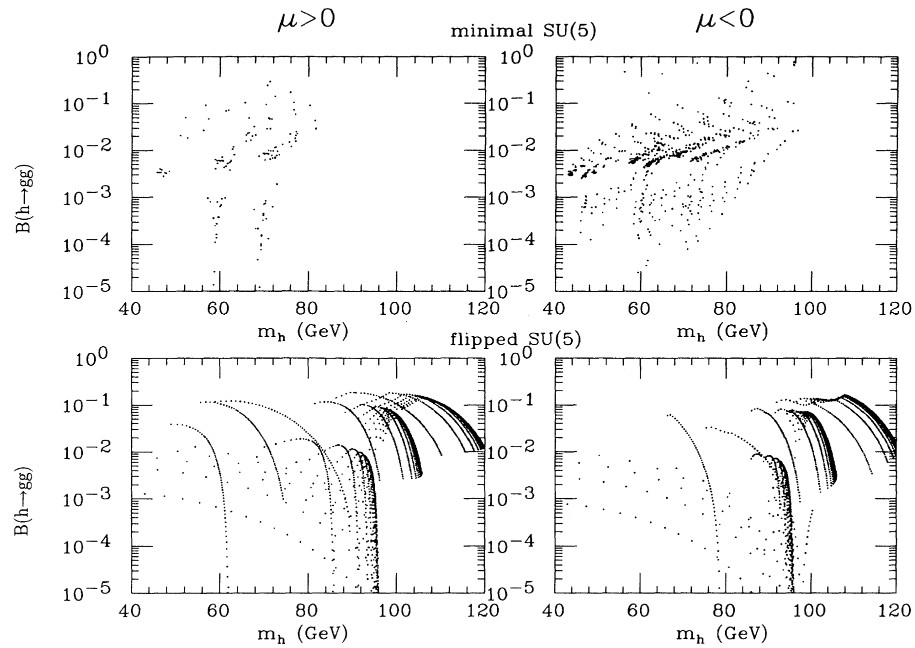

FIG. 11. The branching ratio for $h \to gg$ as a function of the Higgs-boson mass m_h for the minimal SU(5) model (top row) and the flipped model (bottom row). For the minimal SU(5) model note the few points where the branching ratio can be quite large, corresponding to a very light $\tilde{t}_1$.

fraction of h Higgs events compared to the SM will be

$$R_h \equiv \sin^2(\alpha-\beta) f \ , \qquad (4.1)$$

where

$$f \equiv B(h \to X)/B(H_{SM} \to X) \ ,$$

and X is a specific Higgs final state. As for the backgrounds, the various SM $e^+e^- \to ZZ$, W^+W^-, Ze^+e^-, $We\nu_e$, and $q\bar{q}\gamma$ modes apply to a different degree depending on the particular production channel. For the $(h \to jj)\nu\bar{\nu}$ final states we consider here (j = jet), the ZZ, W^+W^-, $q\bar{q}\gamma$, and $We\nu_e$ backgrounds are dominant. Considering the SM analysis first, Ref. [26] finds that for $m_{H_{SM}} \simeq 80$ GeV, the efficiency (ϵ) is $\sim 21\%$ for the dominant $e^+e^- \to H_{SM}Z^* \to (H_{SM} \to b\bar{b})\nu\bar{\nu}$ channel. This corresponds to

$$\sigma(e^+e^- \to Z^* H_{SM} \to \nu\bar{\nu} H_{SM}) \mathcal{L} B(H_{SM} \to b\bar{b}) \epsilon \epsilon_{ISR} = (0.145) \times (500) \times (0.85) \times (0.21) \times (0.91) \approx 12 \qquad (4.2)$$

expected events (ϵ_{ISR} accounts for the initial state radia-

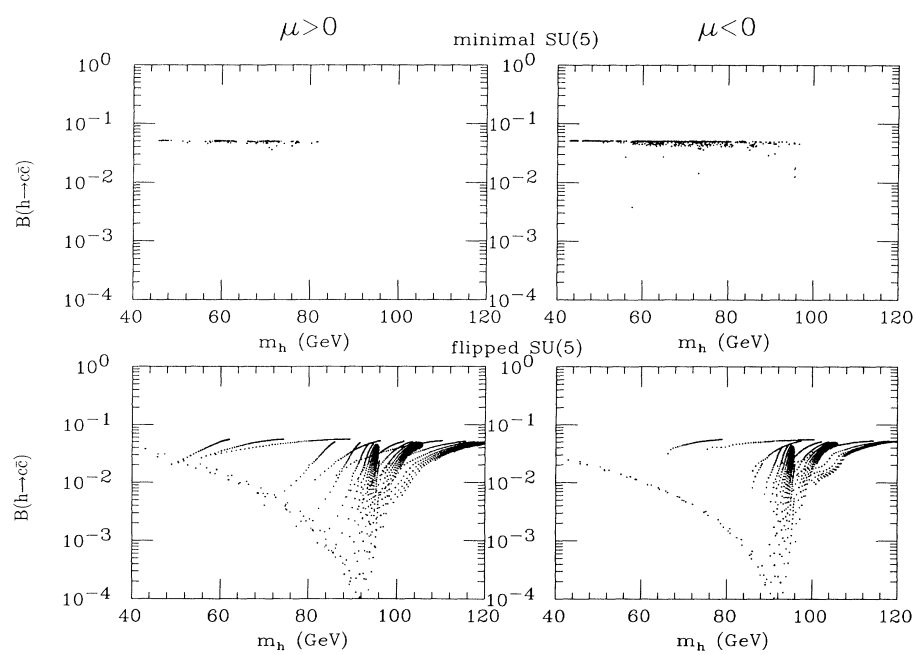

FIG. 12. The branching ratio for $h \to c\bar{c}$ as a function of the Higgs-boson mass m_h for the minimal SU(5) model (top row), and the flipped model (bottom row).

tion effects at $m_{H_{SM}}=80$ GeV) with a background of four events, leading to a signal/background of $\simeq 3$. For $m_{H_{SM}} \gtrsim 80$ GeV, both the signal and efficiency decrease further. Thus, $m_{H_{SM}} \simeq 80$ GeV has until recently been considered the limit of detectability for the SM Higgs.

Turning now to the supersymmetric Higgs analysis, for $m_h < 80$ GeV, we find that $R_h \gtrsim 0.7$ for both models, where

$$f=B(h \to b\bar{b}+c\bar{c}+gg)/B_{SM} .$$

Thus, additional integrated luminosity would be needed in order to probe up to $m_h \simeq 80$ GeV from two-jet reconstruction off the Z via hZ^* production. Despite the degradation of the favored two-jet signal, for $m_h \lesssim 80$ GeV detection via recoil against l^+l^- pairs or two-jets may still be possible through the $e^+e^- \to hZ^* \to (h \to X)l^+l^-$, $(h \to X)jj$ channels, where X is invisible. Overall, a detailed Monte Carlo study would be needed to determine the experimental mass limits for Higgs boson decaying invisibly.

The analysis summarized in Ref. [32] has demonstrated that with b-quark tagging from $H_{SM} \to b\bar{b}$ (and for $\sqrt{s}=190$ GeV), a 90 GeV SM Higgs boson should be detectable above background with $\mathcal{L}=300$ pb^{-1} luminosity at the 5σ level [22]. This extends the experimental Higgs boson reach at LEP even further, through the previously troublesome region where $m_{H_{SM}} \sim M_Z$. For higher beam energies, the Higgs mass reach is expected to be $\sqrt{s}-100$ GeV. If the beam energy could be pushed up to the magnet limit of $\sqrt{s}=240$ GeV, a value of $M_{H_{SM}} \simeq 140$ GeV could, in principle, be explored; however, a reach of $m_{H_{SM}} \lesssim 100$ GeV is more realistic for the near future, corresponding to $\sqrt{s}=200$ GeV.

For $m_h \gtrsim 80$ GeV, we define $f \equiv B(h \to b\bar{b})/B_{SM}$ since b tagging is the only source of the signal. For both models we find the value of R_h can be as small as ~ 0.60 for the experimentally accessible region $m_h \lesssim 100$ GeV.[6] In this case, the irreducible background is certain to obscure the 50–80 % reduction in signal in a b-tagging analysis.

Thus, we conclude that for the minimal SU(5) model and for $\mu>0$, the h Higgs will most likely be seen at LEP II since $m_h \lesssim 83$ GeV and $R_h \gtrsim 0.7$. For $\mu<0$ in the minimal model and for both signs of μ in the flipped model, the h Higgs boson could escape detection at LEP II if 80 GeV $\lesssim m_h \lesssim 100$ GeV and R_h is not big enough, i.e., when the nonstandard hZZ coupling along with the reduction of $B(h \to b\bar{b})$ due to $h \to \chi_1^0\chi_1^0$ is significant, and/or if the $\tilde{t}_1$ is very light, and $h \to gg$ would overwhelm all other channels. It is, of course, possible that for this small set of points ($<1\%$), the associated Higgs boson production processes $e^+e^- \to hA \to b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$ may open up and allow for Higgs boson detection [32]. We must conclude that in the flipped model that we have considered here, it is possible (but unlikely) that nature could conspire to fall within the so-called "tie" region in the $(\tan\beta, m_A)$ plane where neither process could be seen at LEP II. In this unlikely event, the h (and/or the A Higgs) could conceivably escape detection. (For the minimal model $m_A \gg M_Z$ and the "tie" region is avoided entirely.) For the flipped model (and for light $m_A \gtrsim m_h$) in the mass region $m_h > 80$ GeV, the only possible hope would be looking for the h at a 500 GeV e^+e^- machine or at the SCC and/or LHC [18,33].

The present lower bound for the h Higgs is $m_h > 43$ GeV [34]. This limit is regarded as *model independent,* valid for $m_{\tilde{q}} < 1$ TeV, and assumes SM final-state products. In the models we consider here, we have shown that the $h \to \chi_1^0\chi_1^0$ mode should also be considered for some regions of parameter space. One can see, however, from Fig. 9 that for $m_h \lesssim 43$ GeV the $h \to \chi_1^0\chi_1^0$ mode is relatively unimportant. Even for $m_h \lesssim 60$ GeV, the nonstandard reduction of $B(h \to b\bar{b}, c\bar{c}, gg)$ is less than $\approx 15\%$, and we expect a drop in the upper limit to m_h compared to $m_{H_{SM}}$ of only ~ 1 GeV. Coupled with the very SM-like h production (see Fig. 8) for $m_h \lesssim 60$ GeV, and $R_h \gtrsim 0.85$, we find that the $m_{H_{SM}} > 60$ GeV limit also applies to the h Higgs of both the minimal and flipped SU(5) models. For a more detailed discussion of h Higgs mass limits at LEP I in the two models we consider here, see Ref. [11].

V. DISCUSSION AND CONCLUSION

In this paper we have studied the most promising signals for supersymmetry at LEP II in the context of two well motivated supergravity models: (i) the minimal SU(5) supergravity model including the stringent constraints from proton stability and a not too young universe, and (ii) a recently proposed string-inspired no-scale flipped SU(5) supergravity model. These signals involve the neutralino chargino, slepton, and Higgs sectors. Because of the study of *specific* models, we are led to modifications in the standard assumptions regarding sparticle and Higgs boson decay. In the first sector we computed the number of "mixed" (1 lepton + 2 jets + $\not{p}$) events occurring in the decay of pair-produced charginos ($\chi_1^\pm$) and found that the predictions for both models should lead to detection (with $\mathcal{L}=100$ pb^{-1}) up to the kinematical limit ($m_{\chi_1^\pm} \lesssim 100$ GeV). Moreover, these predictions do not overlap: the minimal model predictions being larger than the flipped model ones. This result can be directly traced to a characteristically light sneutrino spectrum in the flipped case ($m_{\tilde{\nu}} \simeq 0.3 m_{\tilde{g}}$). This implies that if $m_{\chi_1^\pm} < 100$ GeV then LEP II should be able to exclude at least one of the two models. In fact, in the minimal SU(5) model $m_{\chi_1^\pm} < 104$ (92) GeV for $\mu > 0$ ($\mu < 0$), assuming $m_{\tilde{q},\tilde{g}} \lesssim 1$ TeV, while in the flipped case $m_{\tilde{\chi}_1^\pm} \lesssim 285$ GeV ($\mu>0, \mu<0$) and the mixed chargino signature can be suppressed. Consequently, it is possible to explore nearly all of the allowed parameter space for the

[6]We exclude from the discussion the very few points for $\mu<0$ in the minimal SU(5) model where $B(h \to gg) \approx 0.9$ and the f ratio drops to values as low as 0.25.

minimal SU(5) model but only $\lesssim 20\%$ of the flipped model.

We found significant chargino-dilepton even rates (per $\mathcal{L}=500$ pb^{-1} for $m_{\chi_1^\pm}>100$ GeV) in the flipped model, and a negligible signal in the minimal model. The question of backgrounds to this process remains open. The magnitude of the experimental efficiency cut for this dilepton signal is not known at present. In the models we consider, the relations among the neutralino and chargino masses $m_{\chi_1^\pm}\approx m_{\chi_1^0}\approx 2m_{\chi_1^0}$ (see Table I) imply that the $e^+e^-\to\chi_1^0\chi_2^0$ process could, in principle, explore indirectly chargino masses up to ~ 130 GeV.

The slepton sector could be kinematically accessible at LEP II only in the flipped SU(5) model. We studied

$$e^+e^-\to\tilde{e}_L^+\tilde{e}_L^- + \tilde{e}_R^+\tilde{e}_R^- + \tilde{e}_L^\pm\tilde{e}_R^\mp$$

and obtained significant numbers of dielectron events which may allow exploration of the full kinematical range with $\mathcal{L}=500$ pb^{-1}. Smuon and stau production are suppressed but may be observable as well. Correlating the slepton and chargino sectors we observed that slepton-dileptons could probe indirectly chargino masses as high as ~ 150 GeV, and thus $\sim 50\%$ of the allowed parameter space. This is especially important for this (the flipped) model since a significant number of points in parameter space for $m_{\chi_1^\pm}<100$ GeV yield negligible mixed chargino event signatures. We also discussed the impact of chargino-dileptons on the slepton-dileptons and the possibilities for experimental discrimination of these signals. For an analysis of the *total* dilepton signal from all supersymmetric sources in these models see Ref. [35].

In the Higgs sector we found that the cross section $e^+e^-\to Z^*h$ deviates negligibly from the SM result in the minimal model, whereas it can be as much as $\frac{1}{3}$ lower in the flipped model. Also, the usually neglected invisible model $h\to\chi_1^0\chi_1^0$ can erode the preferred $h\to b\bar{b},c\bar{c},gg$ ($h\to b\bar{b}$) for $m_h\lesssim 80$ GeV ($m_h\gtrsim 80$ GeV) by as much as 30% (15%) [40% (40%)] in the minimal (flipped) model. The $h\to gg$ mode is usually below ≈ 0.2 although there are exceptional points in the minimal model where it can be much larger, because of a very light $\tilde{t}_1$.

We have recently shown [11] that the current experimental lower bound on the SM Higgs-boson mass ($m_{H_{\rm SM}}>60$ GeV) applies as well to both supergravity models considered here and is therefore more stringent than the supposedly model-independent experimental lower bound $m_h>43$ GeV. In this connection, we have found it useful to relate the results obtained in the chargino sector (as shown in Fig. 3) with those obtained in the Higgs sector by plotting the number of mixed events in chargino pair production versus the Higgs-boson mass; this is shown in Fig. 13. With this plot it is straightforward to determine which points of interest in the chargino sector become excluded by an increasing lower bound on the Higgs-boson mass. In particular, all points for

TABLE I. Comparison of the most important features describing the minimal SU(5) supergravity model and the no-scale flipped SU(5) supergravity model.

Minimal SU(5) supergravity model	No-scale flipped SU(5) supergravity model
Not easily string derivable, no known examples	Easily string derivable, several known examples
Symmetry breaking to the standard model due to the vacuum expectation value (VEV) of **24** and independent of supersymmetry breaking	Symmetry breaking to standard model due to VEV's of **10**,$\overline{\mathbf{10}}$ and tied to onset of supersymmetry breaking
No simple mechanism for doublet-triplet splitting	Natural doublet-triplet splitting mechanism
No-scale supergravity excluded	No-scale supergravity by construction
$m_{\tilde{q}},m_{\tilde{g}}<1$ TeV by *ad hoc* choice: naturalness	$m_{\tilde{q}},m_{\tilde{g}}<1$ TeV by no-scale mechanism
Parameters 5: $m_{1/2},m_0,A,\tan\beta,m_t$	Parameters 3: $m_{1/2},\tan\beta,m_t$
Proton decay: $d=5$ large, strong constraints needed	Proton decay: $d=5$ very small
Dark matter: $\Omega_\chi h_0^2\gg 1$ for most of the parameter space, strong constraints needed	Dark matter: $\Omega_\chi h_0^2\lesssim 0.25$, ok with cosmology and big enough for dark matter problem
$1\lesssim\tan\beta\lesssim 3.5$, $m_t<180$ GeV, $\xi_0\gtrsim 6$	$2\lesssim\tan\beta\lesssim 32$, $m_t<190$ GeV, $\xi_0=0$
$m_{\tilde{g}}\lesssim 400$ GeV	$m_{\tilde{g}}\lesssim 1$ TeV, $m_{\tilde{q}}\approx m_{\tilde{g}}$
$m_{\tilde{q}}>m_{\tilde{l}}>2m_{\tilde{g}}$	$m_{\tilde{l}_L}\approx m_{\tilde{\nu}}\approx 0.3m_{\tilde{g}}\lesssim 300$ GeV $m_{\tilde{l}_R}\approx 0.18m_{\tilde{g}}\lesssim 200$ GeV
$2m_{\chi_1^0}\sim m_{\chi_2^0}\sim m_{\chi_1^\pm}\sim 0.3m_{\tilde{g}}\lesssim 100$ GeV	$2m_{\chi_1^0}\sim m_{\chi_2^0}\approx m_{\chi_1^\pm}\sim 0.3m_{\tilde{g}}\lesssim 285$ GeV
$m_{\chi_3^0}\sim m_{\chi_4^0}\sim m_{\chi_2^\pm}\sim\lvert\mu\rvert$	$m_{\chi_3^0}\sim m_{\chi_4^0}\sim m_{\chi_2^\pm}\sim\lvert\mu\rvert$
60 GeV $<m_h\lesssim 100$ GeV	60 GeV $<m_h\lesssim 135$ GeV
No analogue	Strict no-scale: $\tan\beta=\tan\beta(m_{\tilde{g}},m_t)$ $m_t\lesssim 135$ GeV $\Longrightarrow\mu>0,m_h\lesssim 100$ GeV $m_t\gtrsim 140$ GeV $\Longrightarrow\mu<0,m_h\gtrsim 100$ GeV
Cosmic baryon asymmetry?	Cosmic baryon asymmetry explained [36]

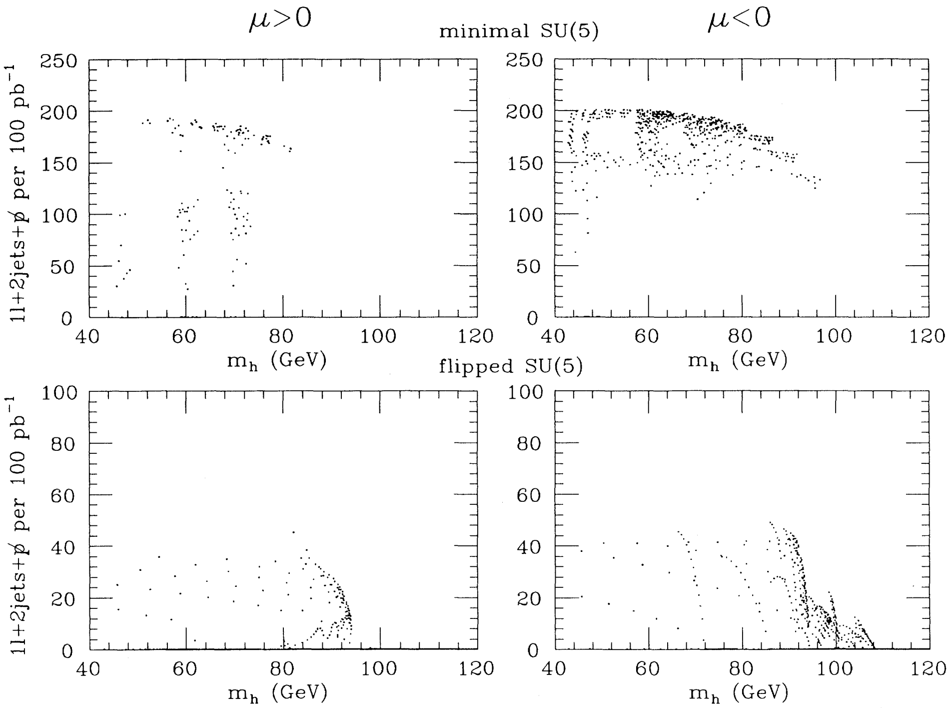

FIG. 13. The number of mixed chargino events as shown in Fig. 3 but versus the lightest Higgs-boson mass instead. All points with $m_h < 60$ GeV are actually experimentally excluded.

$m_h < 60$ GeV are actually experimentally excluded. At LEP II, if no Higgs events are seen for $m_h \lesssim 80$ GeV, Fig. 13 shows that in the minimal model $\gtrsim 125(l+2j+\not{p})$ events are expected. This would allow to unambiguously test these models. In fact, the number of mixed chargino events seen is predicted to be different in the two models for the same Higgs-boson mass limit.

We conclude that the charged slepton sector is a deeper probe than the chargino, neutralino, or Higgs sectors of the flipped SU(5) model at LEP II, while the opposite is true for the minimal SU(5) model where the slepton sector is no probe at all. The interconnections among the various sectors of the models should make them easily falsifiable, or, if verified experimentally, hard to dismiss as coincidences thus providing firm evidence for the underlying structure of these models.

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[1] J. Ellis, S. Kelley, and D. V. Nanopoulos, Phys. Lett. B **249**, 441 (1990); **260**, 131 (1991); Nucl. Phys. **B373**, 55 (1992); P. Langacker and M.-X. Luo, Phys. Rev. D **44**, 817 (1991); U. Amaldi, W. de Boer, and A. Furstenau, Phys. Lett. B **260**, 447 (1991); F. Anselmo, L. Cifarelli, A. Peterman, and A. Zichichi, Nuovo Cimento **104A**, 1817 (1991); **105A**, 581 (1992); H. Arason *et al.*, Phys. Rev. Lett. **67**, 2933 (1991); R. Barbieri and L. Hall, *ibid.* **68**, 752 (1992); A. Giveon, L. Hall, and U. Sarid, Phys. Lett. B **271**, 138 (1991); G. Ross and R. Roberts, Nucl. Phys. **B377**, 571 (1992).

[2] M. Matsumoto, J. Arafune, H. Tanaka, and K. Shiraishi, Phys. Rev. D **46**, 3966 (1992).

[3] R. Arnowitt and P. Nath, Phys. Rev. Lett. **69**, 725 (1992); P. Nath and R. Arnowitt, Phys. Lett. B **287**, 89 (1992); **289**, 368 (1992).

[4] J. L. Lopez, D. V. Nanopoulos, and H. Pois, Phys. Rev. D **47**, 2468 (1993).

[5] J. Hisano, H. Murayama, and T. Yanagida, Phys. Rev. Lett. **69**, 1014 (1992); Nucl. Phys. **B402**, 46 (1993).

[6] J. L. Lopez, D. V. Nanopoulos, H. Pois, and A. Zichichi, Phys. Lett. B **299**, 262 (1993).

[7] J. L. Lopez, D. V. Nanopoulos, and A. Zichichi, Phys. Lett. B **291**, 255 (1992).

[8] R. Arnowitt and P. Nath, Phys. Lett. B **299**, 58 (1993); **307**, 408(E) (1993); Phys. Rev. Lett. **70**, 3696 (1993).

[9] J. L. Lopez, D. V. Nanopoulos, and A. Zichichi, Texas A&M University Report Nos. CTP-TAMU-68/92, CERN-TH.6667/92, and CERN-PPE/92-188 (unpublished).

[10] J. L. Lopez, D. V. Nanopoulos, X. Wang, and A. Zichichi, Phys. Rev. D **48**, 2062 (1993).

[11] J. L. Lopez, D. V. Nanopoulos, H. Pois, X. Wang, and A. Zichichi, Phys. Lett. B **306**, 73 (1993).
[12] D. Dicus, S. Nandi, W. Repko, and X. Tata, Phys. Rev. Lett. **51**, 1030 (1983); X. Tata and D. Dicus, Phys. Rev. D **35**, 2110 (1987); H. Baer, A. Bartl, D. Karatas, W. Majerotto, and X. Tata, Int. J. Mod. Phys. A **4**, 4111 (1989).
[13] T. Schimert, C. Burgess, and X. Tata, Phys. Rev. D **32**, 707 (1985); A. Bartl, H. Fraas, W. Majerotto, and B. Mosslacher, Z. Phys. C **55**, 257 (1992).
[14] A. Bartl, H. Fraas, and W. Majerotto, Z. Phys. C **30**, 441 (1986).
[15] C. Dionisi *et al.*, in *Proceedings of the ECFA Workshop on LEP 200,* Aachen, West Germany, 1986, edited by A. Böhm and W. Hoogland (CERN Report No. 87-08, Geneva, Switzerland, 1987), p. 380.
[16] M. Chen, C. Dionisi, M. Martinez, and X. Tata, Phys. Rep. **159**, 201 (1988).
[17] M. Felcini, in "Ten years of susy confronting experiment," Report No. CERN-TH.6707/92-PPE/92-180, 1992 (unpublished).
[18] J.-F. Grivaz, LAL Report No. 92-64 (unpublished).
[19] D. Dicus, S. Nandi, W. Repko, and X. Tata, Phys. Rev. D **29**, 1317 (1984); A. Bartl, H. Fraas, and W. Majerotto, Nucl. Phys. **B278**, 1 (1986).
[20] M. Gluck and E. Reya, Phys.Rev. D **31**, 1581 (1985); T. Schimert and X. Tata, *ibid.* **32**, 721 (1985).
[21] A. Bartl, H. Fraas, and M. Majerotto, Z. Phys. C **34**, 411 (1987).
[22] S. Katsanevas, talk given at the 1993 Aspen Winter Conference (unpublished).
[23] J. Gunion, H. Haber, G. Kane, and S. Dawson, *The Higgs Hunter's Guide* (Addison-Wesley, Redwood City, 1990).
[24] Y. Okada, M. Yamaguchi, and T. Yanagida, Prog. Theor. Phys. **85**, 1 (1991); Phys. Lett. B **262**, 54 (1991); J. Ellis, G. Ridolfi, and F. Zwirner, *ibid.* **257**, 83 (1991); H. Haber and R. Hempfling, Phys. Rev. Lett. **66**, 1815 (1991).
[25] S. Kelley, J. L. Lopez, D. V. Nanopoulos, H. Pois, and K. Yuan, Nucl. Phys. **B398**, 3 (1993).
[26] S. L. Wu *et al.*, in *Proceedings of the ECFA Workshop on LEP 200* [15], p. 312.
[27] S. Kelley, J. L. Lopez, D. V. Nanopoulos, H. Pois, and K. Yuan, Phys. Lett. B **285**, 61 (1992).
[28] E. Braaten and J. P. Leveille, Phys. Rev. D **22**, 715 (1980); M. Drees and K. Hikasa, Phys. Lett. B **240**, 455 (1990); S. G. Gorishny *et al.*, Mod. Phys. Lett. A **5**, 2703 (1990).
[29] V. Barger, M. S. Berger, A. L. Stange, and R. J. N. Phillips, Phys. Rev. D **45**, 4128 (1992).
[30] T. J. Weiler and T. C. Yuan, Nucl. Phys. **B318**, 337 (1989).
[31] Z. Kunszt and F. Zwirner, Nucl. Phys. **B385**, 3 (1992).
[32] D. Treille, in "Ten years of susy confronting experiment," Report No. CERN-TH.6707/92-PPE/92-180, 1992 (unpublished).
[33] V. Barger, K. Cheung, R. J. N. Phillips, and A. L. Stange, Phys. Rev. D **46**, 4914 (1992).
[34] J.-F. Grivaz, in "Ten years of susy confronting experiment," Report No. CERN-TH.6707/92-PPE/92-180, 1992 (unpublished).
[35] F. Anselmo *et al.*, CERN report (unpublished).
[36] J. Ellis, D. V. Nanopoulos, and K. Olive, Phys. Lett. B **300**, 121 (1993).