CERN-TH.5173/88

ON THE PRODUCTION OF NEUTRALINOS AT THE Z and W AND THEIR DECAY INTO HIGGS BOSONS

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ABSTRACT

Numerical predictions for the decays of the Z and W bosons into neutralinos and charginos and the possible decays of the heavier neutralinos are given within the minimal supersymmetric extension of the standard model. Particular attention is paid to the neutralino decay into Higgs bosons. The regions of supersymmetric parameter space are indicated where a sizeable branching ratio of Z or W decays into neutralinos occurs and the neutralinos dominantly decay into Higgs particles.

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CERN-TH.5173/88
September 1988

In the phenomenology of N = 1 supergravity extensions of the standard electroweak theory [1], neutralinos $\tilde{\chi}^\circ_i$ and charginos $\tilde{\chi}^\pm_i$ play an important rôle. These particles are the neutral and charged mass eigenstates of the gauge and Higgs fermion system and some of them could have masses smaller than the mass of the Z boson. They could be produced through Z or W boson decay at SLC and LEP or at the $Sp\bar{p}S$ and the Tevatron.

For finding supersymmetric particles, a study of their decay properties is as important as that of their production mechanisms [2,3]. The charginos and the heavier neutralinos will decay into ordinary particles and the lightest neutralino $\tilde{\chi}^\circ{}_1$ which is assumed to be the lightest supersymmetric particle. In the minimal supersymmetric extension of the standard model there are scalar and pseudoscalar neutral Higgs bosons, $H^\circ{}_2$ and $H^\circ{}_3$, which could also be lighter than the Z boson [4-6]. One possible interesting decay mode is therefore the two-body decay of a heavier neutralino $\tilde{\chi}^\circ_i$ ($i\neq 1$) into $\tilde{\chi}^\circ{}_1$ and $H^\circ{}_2$ or $H^\circ{}_3$. If $\tilde{\chi}^\circ_i$ is lighter than the squarks and sleptons as well as the Z boson, there are no other two-body decay modes of $\tilde{\chi}^\circ_i$ at the tree level. Then $\tilde{\chi}^\circ{}_i$ would dominantly decay into $\tilde{\chi}^\circ{}_1 H^\circ{}_2$ and/or $\tilde{\chi}^\circ{}_1 H^\circ{}_3$. The neutralino decay will become an efficient process for producing the Higgs boson [5,7]. Supersymmetric theories may be examined by detecting the Higgs particles.

In this letter we study the production of neutralinos at the Z and W resonance, and their two- and three-body decays paying particular attention to the transition $\tilde{\chi}^\circ_i \to H^\circ{}_{2,3} + \tilde{\chi}^\circ{}_1$. We indicate the regions of the supersymmetric parameter space where sizeable branching ratios may be obtained. We shall work within the minimal supersymmetric extension of the standard model [1] and, for definiteness, assume that sleptons, squarks and gluinos are heavier than the Z boson.

The properties of the neutralinos and charginos are determined by four unknown quantities M, M', μ and v_2/v_1 ($\equiv\tan\beta$): M and M' are the masses of SU(2) and U(1) gauge fermions, respectively; μ is the mass parameter of Higgs fermions; and v_1 and v_2 are the vacuum expectation values of two Higgs doublets with U(1) hypercharge $-\frac{1}{2}$ and $+\frac{1}{2}$, respectively. We assume a grand unification scheme where M and M' are related to each other, $M' = (5/3)\tan^2\theta_W M$. Since the model contains two Higgs doublets, there exist five physical Higgs bosons; two neutral scalars $H^\circ{}_1$ and $H^\circ{}_2$, a pseudoscalar $H^\circ{}_3$ and a charged pair $H^\pm$. Their properties are determined by two parameters for which we can take $\tan\beta$ and one of the Higgs boson masses [4,5], for instance that of $H^\circ{}_3$. Then the masses of $H^\circ{}_1$, $H^\circ{}_2$ and $H^\pm$ are given by

$$m^2_{H^\circ_1(H^\circ_2)} = \frac{1}{2}\left\{ m^2_{H^\circ_3} + M_Z^2 \mathop{\pm}_{(-)} \sqrt{(m^2_{H^\circ_3}+M_Z^2)^2 - 4M_Z^2 m^2_{H^\circ_3}\cos^2 2\beta}\right\} \quad (1)$$

$$m^2_{H^\pm} = m^2_{H^\circ_3} + M_W^2 \quad (2)$$

where we have taken H°_1 as the heavier scalar. From Eqs. (1) and (2) the following constraints on the Higgs boson masses are derived:

$$m_{H^\circ_1} \geq M_Z\ ,\ m_{H^\circ_2} \leq M_Z|\cos 2\beta|\ ,\ m_{H^\pm} \geq M_W \quad (3)$$

The mass of H°_2 can become relatively small, especially when $\tan\beta$ is close to one. The second lightest neutralino $\tilde{\chi}^\circ_2$ or the third one $\tilde{\chi}^\circ_3$ produced through the Z boson decay could be heavy enough to decay into $\tilde{\chi}^\circ_1$ and H°_2.

We first consider the decay $Z \to \tilde{\chi}^\circ_i\tilde{\chi}^\circ_j$ [8]. The decay width is given by

$$\Gamma(Z\to\tilde{\chi}^\circ_i\tilde{\chi}^\circ_j) = (2-\delta_{ij})\frac{\alpha_{EM}}{6\sin^2 2\Theta_W} M_Z|F_{ij}|^2\sqrt{1-2\left(\frac{m_i^2}{M_Z^2}+\frac{m_j^2}{M_Z^2}\right)+\left(\frac{m_i^2}{M_Z^2}-\frac{m_j^2}{M_Z^2}\right)^2}$$

$$\cdot\left\{1-\frac{1}{2}\left(\frac{m_i^2}{M_Z^2}+\frac{m_j^2}{M_Z^2}\right)-\frac{1}{2}\left(\frac{m_i^2}{M_Z^2}-\frac{m_j^2}{M_Z^2}\right)^2-3\eta_i\eta_j\frac{m_i m_j}{M_Z^2}\right\} \quad (4)$$

$$|F_{ij}|^2 = \left\{(N_{i3}N_{j3}-N_{i4}N_{j4})\cos 2\beta + (N_{i3}N_{j4}+N_{i4}N_{j3})\sin 2\beta\right\}^2 \quad (5)$$

where N_{ij} is the unitary 4×4 matrix (in the $\tilde{\gamma}$, $\tilde{Z}$, $\tilde{H}_a$, $\tilde{H}_b$ basis) which diagonalizes the mass matrix of the neutral gauge and Higgs fermions. Assuming CP invariance, the mass eigenvalue of $\tilde{\chi}^\circ_i$ is represented as $\eta_i m_i$ with $m_i \geqq 0$ and $\eta_i = \pm 1$ [9]. The details and notation are given in Ref. [2]. The decay width $\Gamma(Z\to\tilde{\chi}^\circ_i\tilde{\chi}^\circ_j)$ strongly depends on the mixing properties of $\tilde{\chi}^\circ_i$ and $\tilde{\chi}^\circ_j$, because the Z boson only couples to the Higgs fermion components in the neutralinos. These components become large in light neutralinos when $|\mu| \ll M_Z$ and then a sizeable branching ratio for $Z \to \tilde{\chi}^\circ_i\tilde{\chi}^\circ_j$ will be obtained [8].

The branching ratios of $Z \to \tilde{\chi}^\circ_1\tilde{\chi}^\circ_2$, $\tilde{\chi}^\circ_1\tilde{\chi}^\circ_3$, $\tilde{\chi}^\circ_2\tilde{\chi}^\circ_2$ are shown in Figs. 1 and 2 for μ = 20 GeV and M = 20 GeV, respectively. [Note that Eq. (4) is invariant under a sign change of both μ and M; $(\mu,M) \to (-\mu,-M)$.] As the possible decay modes we have taken into account $Z \to \tilde{\chi}^\circ_i\tilde{\chi}^\circ_j$, $Z \to \tilde{\chi}^+_2\tilde{\chi}^-_2$ (a pair of lighter charginos),

$Z \to H^\circ_2 H^\circ_3$ and the ordinary two-body decay modes yielding a pair of leptons and quarks except the top quark. For the mass of the lighter chargino we assume a lower bound of 30 GeV which is slightly above the value obtained from the e^+e^- experiments [10]. When $\mu(M) = 20$ GeV, the allowed regions in the parameter space are -480 GeV $\lesssim M(\mu) \lesssim 60$ GeV for $\tan\beta = 2.0$ and -220 GeV $\lesssim M(\mu) \lesssim -20$ GeV for $\tan\beta = 4.0$. In Fig. 1 for $M \lesssim -90$ GeV the Z boson decays into $\tilde{\chi}^\circ_1$ and a heavier neutralino with a branching ratio between one and seven per cent. For -110 GeV $\lesssim M \lesssim -90$ GeV with $\tan\beta = 2.0$ and -110 GeV $\lesssim M \lesssim -50$ GeV with $\tan\beta = 4.0$ the branching ratio of $Z \to \tilde{\chi}^\circ_1 \tilde{\chi}^\circ_3$ becomes much greater than that of $Z \to \tilde{\chi}^\circ_1 \tilde{\chi}^\circ_2$. The reason is that in these ranges of the parameters $\tilde{\chi}^\circ_3$ is Higgsino-like while $\tilde{\chi}^\circ_2$ is photino-like, whereas for $M \lesssim -110$ GeV $\tilde{\chi}^\circ_2$ is the Higgsino-like state. The lightest neutralino $\tilde{\chi}^\circ_1$ is almost a Higgsino if $|M|$ is large compared to $|\mu|$. For convenience, let us denote by $\tilde{\chi}^\circ_h$ the Higgsino-like state of $\tilde{\chi}^\circ_2$ or $\tilde{\chi}^\circ_3$. It is the decay $Z \to \tilde{\chi}^\circ_1 \tilde{\chi}^\circ_h$ that has a sizeable width. For $M \lesssim -90$ GeV (-50 GeV) and $\tan\beta = 2.0$ (4.0) the masses of $\tilde{\chi}^\circ_1$, $\tilde{\chi}^\circ_2$ and $\tilde{\chi}^\circ_3$ are $m_1 \approx 17$ GeV (12 GeV), 50 GeV (30 GeV) $\lesssim m_2 \lesssim 68$ GeV (65 GeV), $m_3 \gtrsim 68$ GeV (65 GeV). In the ranges -130 GeV $\lesssim M \lesssim -90$ GeV, 0 GeV $\lesssim M$ with $\tan\beta = 2.0$ and -140 GeV $\lesssim M \lesssim -50$ GeV with $\tan\beta = 4.0$, $\tilde{\chi}^\circ_3$ is light enough to be produced by Z boson decay. The invisible decay $Z \to \tilde{\chi}^\circ_1 \tilde{\chi}^\circ_1$ occurs at around one per cent for most values of M except $|M| \lesssim |\mu|$. In Fig. 2, contrary to the case of small $|\mu|$ shown in Fig. 1, the decay into any pair of neutralinos is negligible for large $|\mu|$. For 20 GeV $\lesssim |\mu| \lesssim 60$ GeV (-150 GeV $\lesssim \mu \lesssim -20$ GeV) and $\tan\beta = 2.0$ (4.0) the masses of $\tilde{\chi}^\circ_1$, $\tilde{\chi}^\circ_2$ and $\tilde{\chi}^\circ_3$ are $m_1 \approx 12$ GeV (11 GeV), 15 GeV $\lesssim m_2 \lesssim 43$ GeV (33 GeV), $m_3 \gtrsim 74$ GeV (95 GeV). When both $|\mu|$ and $|M|$ are small, the branching ratio $B(Z \to \tilde{\chi}^\circ_2 \tilde{\chi}^\circ_2)$ may become a few per cent in the region where $\tilde{\chi}^\circ_2$ is mainly composed of Higgs fermions.

The sum of the decay widths of Z into neutralino and chargino pairs for $\mu = 20$ GeV may become 400 MeV. For $\tan\beta = 2.0$ and -130 GeV $\lesssim M \lesssim 10$ GeV the mass of $\tilde{\chi}^\pm_2$ is larger than $M_Z/2$, so that the decay $Z \to \tilde{\chi}^+_2 \tilde{\chi}^-_2$ does not occur. In this case the sum of the decay widths of Z into neutralino pairs is approximately 40 MeV.

If the Higgs bosons H°_2 and H°_3 are light, the Z boson can decay directly into $H^\circ_2 H^\circ_3$ [5,14]. The decay width is given by

$$\Gamma(Z \to H^\circ_2 H^\circ_3) = \frac{\alpha_{EM}}{12 \sin^2 2\theta_W} \cos^2(\alpha-\beta) M_Z \sqrt{\left\{1 - 2\left(\frac{m^2_{H^\circ_2}}{M^2_Z} + \frac{m^2_{H^\circ_3}}{M^2_Z}\right) + \left(\frac{m^2_{H^\circ_2}}{M^2_Z} - \frac{m^2_{H^\circ_3}}{M^2_Z}\right)^2\right\}^3} \quad (6)$$

$$\cos(\alpha-\beta) = -\,\mathrm{sign}(v_2-v_1)\sqrt{\frac{r_2(1-r_2)}{r_3(1-2r_2+r_3)}} \tag{7}$$

where α is a mixing angle arising from the Higgs potential and

$$r_2 = \frac{m^2_{H^\circ_2}}{M_Z^2}\quad , \quad r_3 = \frac{m^2_{H^\circ_3}}{M_Z^2} \tag{8}$$

The Z boson can also decay into $H^\circ_2 f\bar{f}$ through the virtual Z exchange [11,12], where f is a lepton or a quark. In Fig. 3, $B(Z \to H^\circ_2 H^\circ_3)$ is shown as a function of $M_{H^\circ_2}$ for μ = 20 GeV and M = -150 GeV. When $m_{H^\circ_2}$ is 10 GeV, the branching ratio becomes about one per cent. For comparison, also shown in Fig. 3 is the branching ratio $B(Z \to H^\circ_2 f\bar{f})$ summed over all the lepton and quark pairs except $t\bar{t}$.

We have shown that the Z boson decay yields $\tilde{\chi}^\circ_2$ or $\tilde{\chi}_3$ at a sizeable rate in a wide range of M if $|\mu|$ is small. In the N = 1 supergravity model with SU(2)×U(1) symmetry breaking through radiative corrections (for a review, see Ref. [13]), a small value for $|\mu|$ is natural in the sense that no ad hoc way is necessary to generate it [14]. Furthermore, in this model for small $|\mu|$ and large $|M|$ a top quark mass around 60 GeV or more would be preferred [13,15], which is consistent with recent experimental analyses [16]. Then the parameter $\tan\beta$ is not necessarily close to one.

Now we consider the decay of the neutralinos produced by the Z boson decay. The possible decay modes are as follows:

$$\begin{aligned} \tilde{\chi}^\circ_j &\to H^\circ_2\,\tilde{\chi}^\circ_i\ ,\quad H^\circ_3\,\tilde{\chi}^\circ_i \\ &\to f\bar{f}\,\tilde{\chi}^\circ_i \\ &\to \tilde{\chi}^+_2 f\bar{f}'\ ,\quad \tilde{\chi}^-_2 \bar{f} f' \\ &\to \tilde{\chi}^\circ_i\,\tilde{\chi}^\circ_i\,\tilde{\chi}^\circ_i \\ &\to \gamma\,\tilde{\chi}^\circ_i \end{aligned} \tag{9}$$

Here f stands for a quark or a lepton. As we have seen, if $\tilde{\chi}^\circ_2$ or $\tilde{\chi}^\circ_3$ is produced at a sizeable rate, there are two possibilities: (a) $|M| \gtrsim M_Z > |\mu|$, (b) $|M|$, $|\mu| < M_Z$. In case (a) the Z boson decay yields $\tilde{\chi}^\circ_1$ and $\tilde{\chi}^\circ_h$. The mass difference between $\tilde{\chi}^\circ_1$ and $\tilde{\chi}^\circ_h$ is not small (e.g., 33 GeV $\lesssim m_h - m_1 \lesssim$ 57 GeV for -250 GeV $\lesssim M \lesssim$ -90 GeV with $|\mu|$ = 20 GeV and $\tan\beta$ = 2.0), so that the decay

$\tilde{\chi}^\circ_h \to H^\circ_2(H^\circ_3)\tilde{\chi}^\circ_1$ is likely to occur. Among the three-body decays in Eq. (9) the decay $\tilde{\chi}^\circ_h \to f\bar{f}\tilde{\chi}^\circ_1$ will be the dominant one. Since both $\tilde{\chi}^\circ_1$ and $\tilde{\chi}^\circ_h$ are essentially Higgsinos, the decay width for $\tilde{\chi}^\circ_h \to \gamma\tilde{\chi}^\circ_1$ will also be much smaller than that for $\tilde{\chi}^\circ_h \to f\bar{f}\tilde{\chi}^\circ_1$. In case (b) the Z boson decay yields a pair of $\tilde{\chi}^\circ_2$, whose mass is close to the $\tilde{\chi}^\circ_1$ mass (e.g., 3 GeV $\lesssim m_2-m_1 \lesssim$ 16 GeV for -20 GeV $\lesssim M \lesssim$ 20 GeV with $|\mu|$ = 20 GeV and $\tan\beta$ = 2.0). The decay $\tilde{\chi}^\circ_2 \to H^\circ_2\tilde{\chi}^\circ_1$ can therefore not occur unless H°_2 is very light. Since $\tilde{\chi}^\circ_1$ and $\tilde{\chi}^\circ_2$ are essentially a photino and a Higgsino, respectively, the radiative decay $\tilde{\chi}^\circ_2 \to \gamma\tilde{\chi}^\circ_1$ will become comparable to the three-body decays [17]. Therefore the Higgs boson production by neutralino decay is more likely to occur if case (a) is realized, on which our analysis will be focused in the following.

The decay widths for $\tilde{\chi}^\circ_j \to H^\circ_2\tilde{\chi}^\circ_i$ and $\tilde{\chi}^\circ_j \to H^\circ_3\tilde{\chi}^\circ_i$ are given by [7]

$$\Gamma(\tilde{\chi}^\circ_j \to H^\circ_2 \tilde{\chi}^\circ_i) = \frac{\alpha}{4\sin^2 2\theta_W} m_j |G_{ij}|^2 \sqrt{1 - 2\left(\frac{m_i^2}{m_j^2} + \frac{m^2_{H^\circ_2}}{m_j^2}\right) + \left(\frac{m_i^2}{m_j^2} - \frac{m^2_{H^\circ_2}}{m_j^2}\right)^2}$$

$$\cdot\left\{1 + \frac{m_i^2}{m_j^2} - \frac{m^2_{H^\circ_2}}{m_j^2} + 2\eta_i\eta_j\frac{m_i}{m_j}\right\} \tag{10}$$

$$\Gamma(\tilde{\chi}^\circ_j \to H^\circ_3 \tilde{\chi}^\circ_i) = \frac{\alpha}{4\sin^2 2\theta_W} m_j |H_{ij}|^2 \sqrt{1 - 2\left(\frac{m_i^2}{m_j^2} + \frac{m^2_{H^\circ_3}}{m_j^2}\right) + \left(\frac{m_i^2}{m_j^2} - \frac{m^2_{H^\circ_3}}{m_j^2}\right)^2}$$

$$\cdot\left\{1 + \frac{m_i^2}{m_j^2} - \frac{m^2_{H^\circ_3}}{m_j^2} - 2\eta_i\eta_j\frac{m_i}{m_j}\right\} \tag{11}$$

$$|G_{ij}|^2 = \left\{(N_{i2}N_{j3} + N_{i3}N_{j2})\sin(\alpha-\beta) + (N_{i2}N_{j4} + N_{i4}N_{j2})\cos(\alpha-\beta)\right\}^2 \tag{12}$$

$$|H_{ij}|^2 = \left\{(N_{i2}N_{j3} + N_{i3}N_{j2})\sin 2\beta - (N_{i2}N_{j4} + N_{i4}N_{j2})\cos 2\beta\right\}^2 \tag{13}$$

where

$$\sin(\alpha-\beta) = -\sqrt{\frac{(1-r_2+r_3)(r_3-r_2)}{r_3(1-2r_2+r_3)}} \tag{14}$$

For the decay widths of the other modes, see Refs. [2] and [18]. We take 100 GeV for the masses of squarks and sleptons. In Fig. 4 the branching ratios for $\tilde{\chi}^\circ_h \to H^\circ_2\tilde{\chi}^\circ_1$ and $\tilde{\chi}^\circ_h \to H^\circ_3\tilde{\chi}^\circ_1$ are shown for $m_{H^\circ_2}$ = 20 GeV and $m_{H^\circ_2}$ = 40 GeV. When $m_{H^\circ_2}$ is 20 GeV ($m_{H^\circ_3}$ = 35 GeV for tanβ = 2 and $m_{H^\circ_3}$ = 23 GeV for tanβ = 4), the decay $\tilde{\chi}^\circ_h \to H^\circ_2\tilde{\chi}^\circ_1$ is allowed for any value of M considered. The branching ratios for $H^\circ_2\tilde{\chi}^\circ_1$ and $H^\circ_3\tilde{\chi}^\circ_1$ amount together to more than 90 per cent. When $m_{H^\circ_2}$ is 40 GeV ($m_{H^\circ_3}$ = 87 GeV for tanβ = 2 and $m_{H^\circ_3}$ = 47 GeV for tanβ = 4), for $M \lesssim -190$ GeV and tanβ = 2.0 or $M \lesssim -200$ GeV and tanβ = 4.0 both $\tilde{\chi}^\circ_h \to H^\circ_2\tilde{\chi}^\circ_1$ and $\tilde{\chi}^\circ_h \to H^\circ_3\tilde{\chi}^\circ_1$ are kinematically forbidden. In the kinematically allowed region for tanβ = 4.0 $B(\tilde{\chi}^\circ_h \to H^\circ_2\tilde{\chi}^\circ_1)$ and $B(\tilde{\chi}^\circ_h \to H^\circ_3\tilde{\chi}^\circ_1)$ also amount together to more than 90 per cent for most values of M. As an explicit example we show the branching ratios for all decays of $\tilde{\chi}^\circ_h$ for M = −120 GeV and μ = 20 GeV in Table 1. Among the three-body decays, the decay into a pair of quarks has the largest ratio.

Finally, we comment on another possible process for producing the second lightest neutralino. It is the decay of the W boson into a neutralino and the lighter chargino [19,20]. The W boson couples to both Higgs fermions and gauge fermions. So if the decay $W \to \tilde{\chi}^\circ_2\tilde{\chi}^\pm_2$ is kinematically allowed, the decay width will be sizeable for any range of parameters. In Fig. 5 the branching ratios of $W \to \tilde{\chi}^\circ_1\tilde{\chi}^\pm_2$ and $W \to \tilde{\chi}^\circ_2\tilde{\chi}^\pm_2$ are shown for tanβ = 2.0 for the cases $|\mu| < M_Z < |M|$ and $|M| < M_Z < |\mu|$. As possible decay modes we have taken into account $W \to \tilde{\chi}^\circ_i\tilde{\chi}^\pm_2$ and the ordinary decay modes $W \to f\bar{f}'$ except $W \to t\bar{b}$. The branching ratio $B(W \to \tilde{\chi}^\circ_2\tilde{\chi}^\pm_2)$ may become five per cent for μ = 20 GeV and as large as 20 per cent for M = 20 GeV. The mass of $\tilde{\chi}^\pm_2$ is 30 GeV $\lesssim M_2 \lesssim$ 40 GeV for −480 GeV $\lesssim M(\mu) \lesssim$ −200 GeV. When tanβ = 4.0, the decay $W \to \tilde{\chi}^\circ_2\tilde{\chi}^\pm_2$ is kinematically not allowed in the cases stated above. The decay $W \to \tilde{\chi}^\circ_2\tilde{\chi}^\pm_2$ may also be possible if $|\mu| \sim |M| < M_Z$. Since the leptonic decays $\tilde{\chi}^\circ_2 \to \ell\bar{\ell}\tilde{\chi}^\circ_1$ and $\tilde{\chi}^\pm_2 \to \ell\nu\tilde{\chi}^\circ_1$ are possible, W production at $p\bar{p}$ colliders and the subsequent decay $W \to \tilde{\chi}^\circ_2\tilde{\chi}^\pm_2$ may lead to multilepton events. From the absence of such events constraints on the masses of $\tilde{\chi}^\circ_2$ and $\tilde{\chi}^\pm_2$ were derived in Ref. [20]. However, if $\tilde{\chi}^\circ_2$ dominantly decays into $H^\circ_2\tilde{\chi}^\circ_1$ and/or $H^\circ_3\tilde{\chi}^\circ_1$, the multilepton events are suppressed and less strong constraints may be derived.

In conclusion, we have studied the signature of neutralino production by Z and W boson decays. The Z boson can sizeably decay into a pair of neutralinos only when $|\mu|$ is small compared to M_Z. Then in a wide range of M the decay yields $\tilde{\chi}^\circ_1$ and $\tilde{\chi}^\circ_h$ leading to a one-sided event. If there exists a Higgs boson lighter than 30–40 GeV, the decay products of $\tilde{\chi}^\circ_h$ are expected to contain the Higgs boson. These distinctive phenomena will enable us to examine the supersymmetric electroweak model in an important range of parameters.

ACKNOWLEDGEMENTS

One of us (W.M.) wishes to thank the CERN Theoretical Physics Division for its kind hospitality. He also acknowledges an interesting discussion with H.E. Haber. We thank John Ellis for reading the manuscript.

$\tan\beta = 2$, $M = -120$ GeV, $\mu = 20$ GeV			$\tan\beta = 4$, $M = -120$ GeV, $\mu = 20$ GeV	
Particle	Mass (GeV)		Mass (GeV)	
$\tilde{\chi}^\circ_1$	17		12	
$\tilde{\chi}^\circ_h = \tilde{\chi}^\circ_2$	68		65	
$\tilde{\chi}^+_2$	48		34	
H°_2	40 (input)		40 (input)	
H°_3	87		47	
Decay	Width (keV)	BR (%)	Width (keV)	BR (%)
$\tilde{\chi}^\circ_2 \to \nu\bar{\nu}\tilde{\chi}^\circ_1$	18.03	16.23	14.46	0.24
$\ell^+\ell^-\tilde{\chi}^\circ_1$	7.62	6.87	5.34	0.09
$u\bar{u}\tilde{\chi}^\circ_1$	19.54	17.6	14.98	0.25
$d\bar{d}\tilde{\chi}^\circ_1$	33.12	29.82	22.8	0.38
$H^\circ_2\tilde{\chi}^\circ_1$	23.25	20.94	1510	24.88
$H^\circ_3\tilde{\chi}^\circ_1$	-	-	4430	73.04
$\tilde{\chi}^+_2\ell^-\bar{\nu} + \tilde{\chi}^-_2\ell^+\nu$	3.48	3.12	25.08	0.41
$\tilde{\chi}^+_2 d\bar{u} + \chi^-_2\bar{d}u$	5.96	5.36	42.56	0.70
$3\ \tilde{\chi}^\circ_1$	0.07	0.06	0.63	0.01

- TABLE -

Partial widths and branching ratios for the various decay channels of $\tilde{\chi}^\circ_2$ for $M = -120$ GeV, $\mu = 20$ GeV, $m_{H^\circ_2} = 40$ GeV, $\tan\beta = 2$ and $\tan\beta = 4$, respectively. It is summed over all contributing leptons and quark flavours except the top quark. Also shown are the masses resulting from the input parameters.

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FIGURE CAPTIONS

Fig. 1 Branching ratios for Z° decay into neutralino pairs for μ = 20 GeV as a function of M (a) for $\tan\beta$ = 2.0, (b) for $\tan\beta$ = 4.0.
-■- $Z^\circ \to \tilde{\chi}^\circ{}_1\tilde{\chi}^\circ{}_2$, -◆- $Z^\circ \to \tilde{\chi}^\circ{}_1\tilde{\chi}^\circ{}_3$, -□- $Z^\circ \to \tilde{\chi}^\circ{}_2\tilde{\chi}^\circ{}_2$
Also shown is the boundary for chargino mass $M_2 > 30$ GeV.

Fig. 2 Branching ratios for Z° decay into neutralino pairs for M = 20 GeV as a function of μ (a) for $\tan\beta$ = 2.0, (b) for $\tan\beta$ = 4.0.
-■- $Z^\circ \to \tilde{\chi}^\circ{}_1\tilde{\chi}^\circ{}_2$, -◆- $Z^\circ \to \tilde{\chi}^\circ{}_1\tilde{\chi}^\circ{}_3$, -□- $Z^\circ \to \tilde{\chi}^\circ{}_2\tilde{\chi}^\circ{}_2$
Also shown is the boundary for chargino mass $M_2 > 30$ GeV.

Fig. 3 Branching ratios for the decays $Z^\circ \to H^\circ{}_2H^\circ{}_3$ and $Z^\circ \to H^\circ{}_2f\bar{f}$ summed over all lepton and quark pairs (except $t\bar{t}$), for μ = 20 GeV and M = -150 GeV, versus the mass of $H^\circ{}_2$. -■- $Z^\circ \to H^\circ{}_2H^\circ{}_3$ $\tan\beta$ = 2.0, -◆- $Z^\circ \to H^\circ{}_2H^\circ{}_3$ $\tan\beta$ = 4.0, -□- $Z^\circ \to H^\circ{}_2f\bar{f}$ $\tan\beta$ = 2.0, -◇- $Z^\circ \to H^\circ{}_2f\bar{f}$ $\tan\beta$ = 4.0.

Fig. 4 Branching ratios for the decays of the Higgsino-like neutralino $\tilde{\chi}^\circ{}_h \to H^\circ{}_2\tilde{\chi}^\circ{}_1$ and $\tilde{\chi}^\circ{}_h \to H^\circ{}_3\tilde{\chi}^\circ{}_1$ for μ = 20 GeV as a function of M, (a) for $\tan\beta$ = 2.0, (b) for $\tan\beta$ = 4.0.
-■- $\tilde{\chi}^\circ{}_h \to H^\circ{}_2\tilde{\chi}^\circ{}_1$, $m_{H^\circ{}_2}$ = 20 GeV, -◆- $\tilde{\chi}^\circ{}_h \to H^\circ{}_3\tilde{\chi}^\circ{}_1$, $m_{H^\circ{}_2}$ = 20 GeV,
-□- $\tilde{\chi}^\circ{}_h \to H^\circ{}_2\tilde{\chi}^\circ{}_1$, $m_{H^\circ{}_2}$ = 40 GeV, -◇- $\tilde{\chi}^\circ{}_h \to H^\circ{}_3\tilde{\chi}^\circ{}_1$, $m_{H^\circ{}_2}$ = 40 GeV.
For M < -110 GeV: $\tilde{\chi}^\circ{}_h = \tilde{\chi}^\circ{}_2$, for M > -110 GeV: $\tilde{\chi}^\circ{}_h = \tilde{\chi}^\circ{}_3$.

Fig. 5 Branching ratios for W decays into chargino and neutralino for $\tan\beta$ = 2 and μ = 20 GeV (M = 20 GeV) as a function of M(μ).
-■- $W^\pm \to \tilde{\chi}^\pm{}_2\tilde{\chi}^\circ{}_1$ (μ = 20 GeV), -◆- $W^\pm \to \tilde{\chi}^\pm{}_2\tilde{\chi}^\circ{}_2$ (μ = 20 GeV),
-□- $W^\pm \to \tilde{\chi}^\pm{}_2\tilde{\chi}^\circ{}_1$ (M = 20 GeV), -◇- $W^\pm \to \tilde{\chi}^\pm{}_2\tilde{\chi}^\circ{}_2$ (M = 20 GeV).
Also shown is the boundary for chargino mass $M_2 > 30$ GeV.

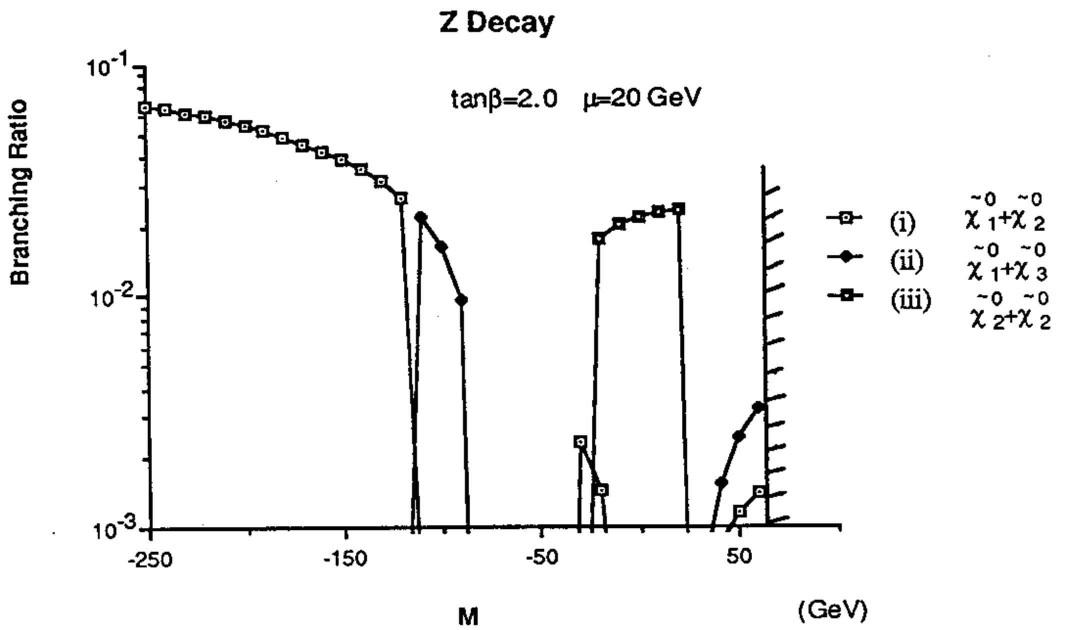

Z Decay
tanβ=2.0 μ=20 GeV
Branching Ratio
10-1
10-2
10-3
-250
-150
-50
50
M
(GeV)
(i) χ̃⁰1+χ̃⁰2
(ii) χ̃⁰1+χ̃⁰3
(iii) χ̃⁰2+χ̃⁰2

Fig. 1(a)

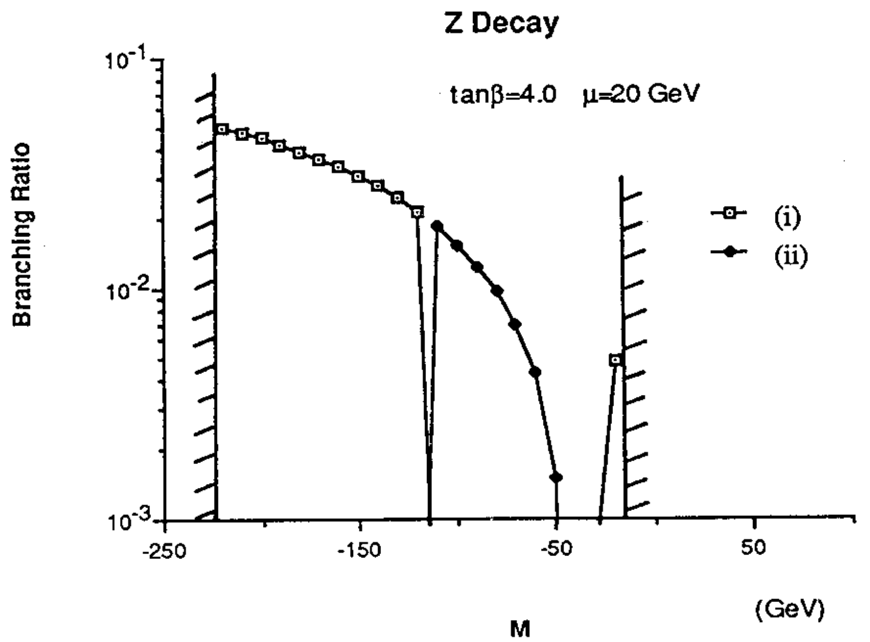

Z Decay
tanβ=4.0 μ=20 GeV
Branching Ratio
10-1
10-2
10-3
-250
-150
-50
50
M
(GeV)
(i)
(ii)

Fig. 1(b)

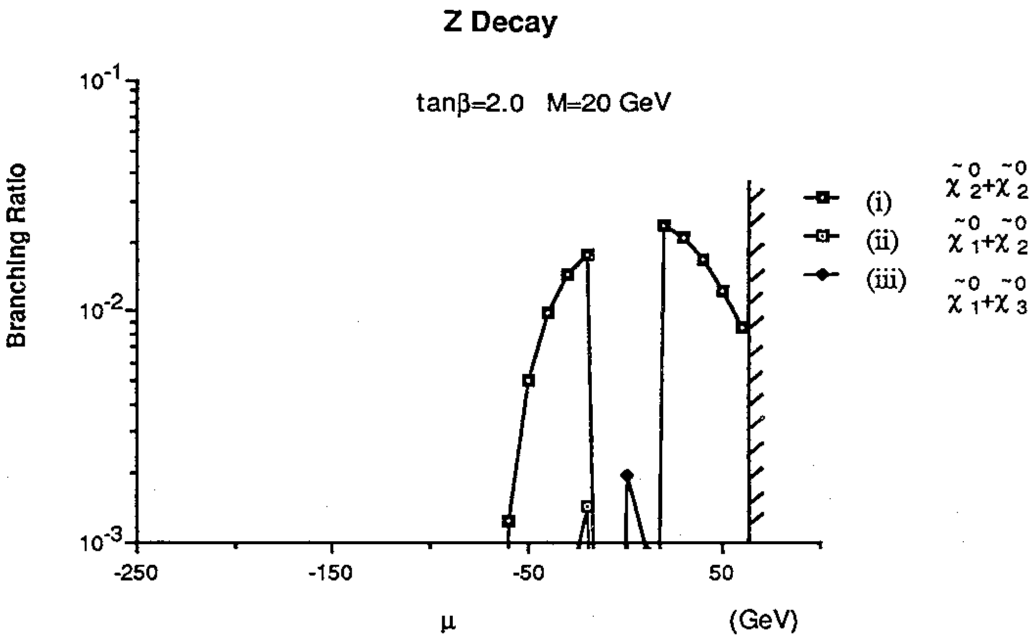

Z Decay
tanβ=2.0 M=20 GeV
Branching Ratio
10^{-1}
10^{-2}
10^{-3}
-250
-150
-50
50
μ
(GeV)
(i) $\tilde{\chi}^0_2+\tilde{\chi}^0_2$
(ii) $\tilde{\chi}^0_1+\tilde{\chi}^0_2$
(iii) $\tilde{\chi}^0_1+\tilde{\chi}^0_3$

Fig. 2(a)

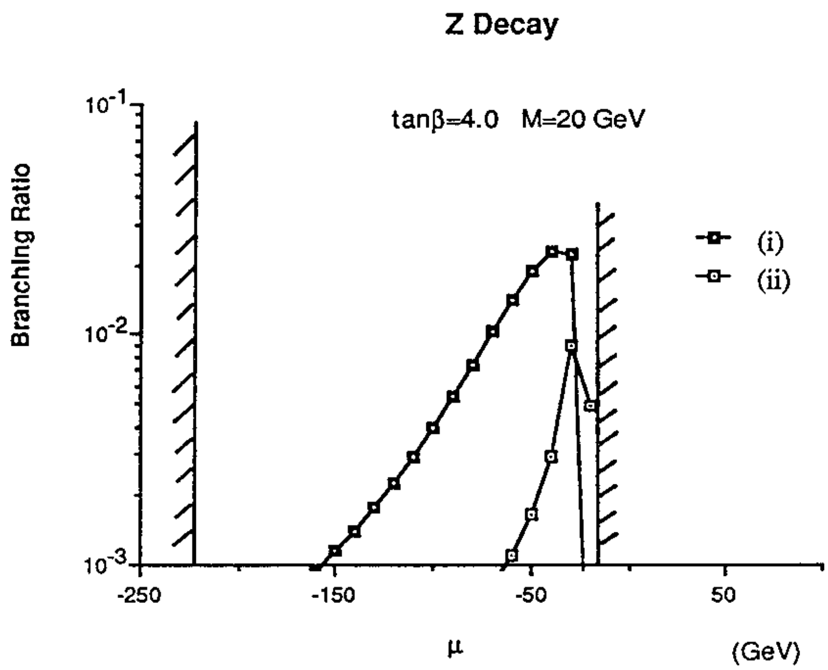
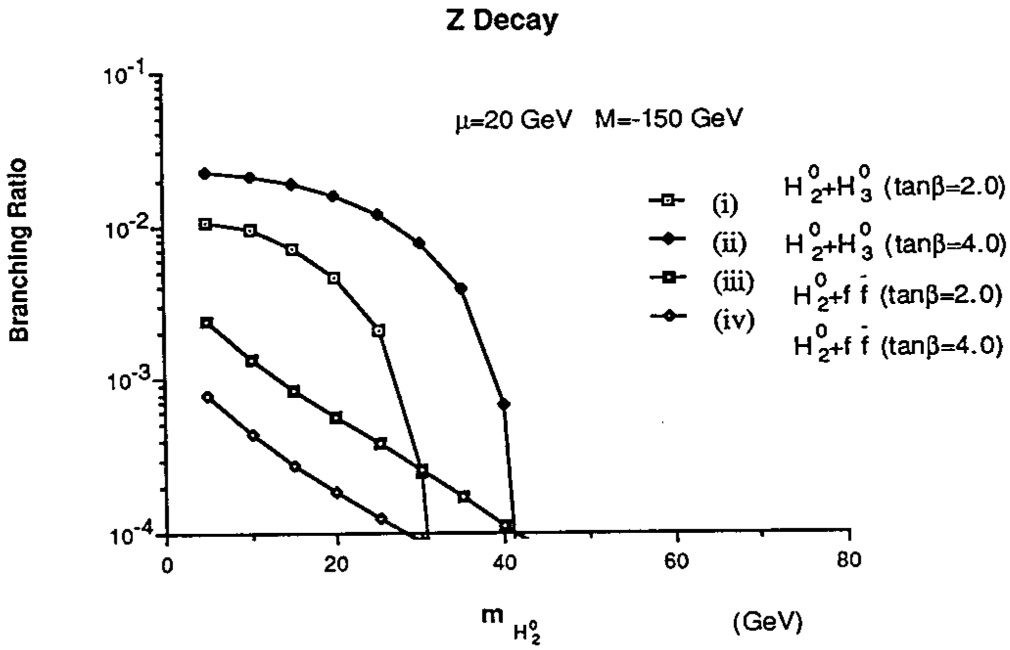

Z Decay
tanβ=4.0 M=20 GeV
Branching Ratio
10^{-1}
10^{-2}
10^{-3}
-250
-150
-50
50
μ
(GeV)
(i)
(ii)

Fig. 2(b)



Z Decay
μ=20 GeV M=-150 GeV
Branching Ratio
10⁻¹
10⁻²
10⁻³
10⁻⁴
0
20
40
60
80
(i) $H_2^0+H_3^0$ (tanβ=2.0)
(ii) $H_2^0+H_3^0$ (tanβ=4.0)
(iii) $H_2^0+f\bar{f}$ (tanβ=2.0)
(iv) $H_2^0+f\bar{f}$ (tanβ=4.0)
$m_{H_2^0}$ (GeV)

Fig. 3

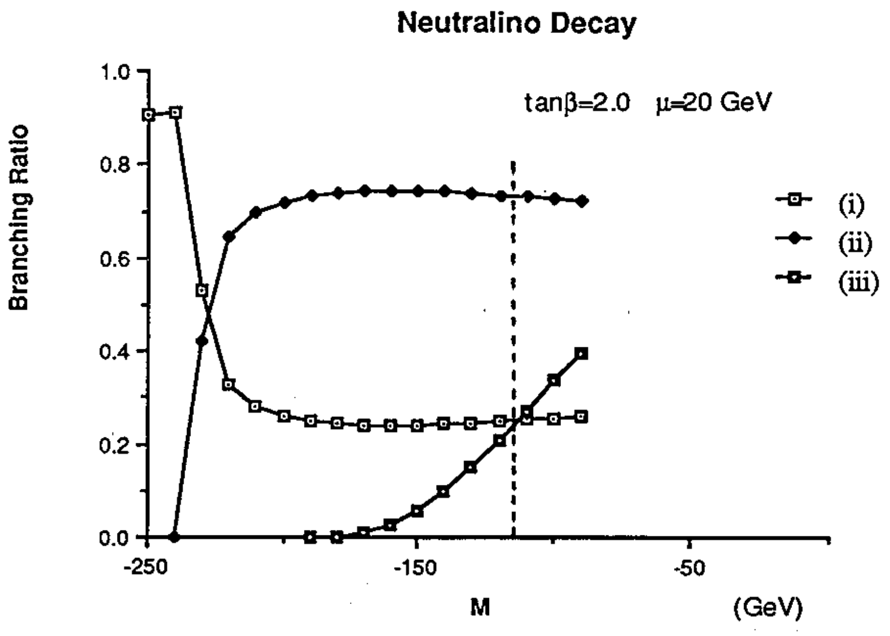

Neutralino Decay
tanβ=2.0 μ=20 GeV
Branching Ratio
1.0
0.8
0.6
0.4
0.2
0.0
-250
-150
-50
M
(GeV)
(i)
(ii)
(iii)

Fig. 4(a)

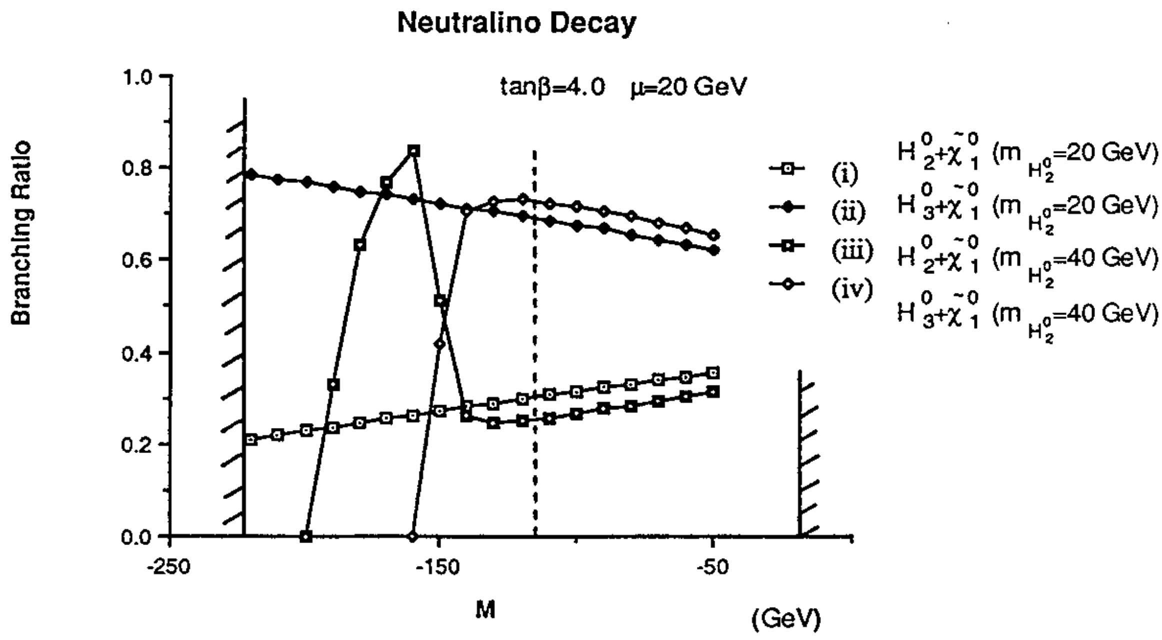

Neutralino Decay
tanβ=4.0 μ=20 GeV
Branching Ratio
1.0
0.8
0.6
0.4
0.2
0.0
-250
-150
-50
M
(GeV)
(i) $H^0_2+\tilde{\chi}^0_1$ ($m_{H^0_2}$=20 GeV)
(ii) $H^0_3+\tilde{\chi}^0_1$ ($m_{H^0_2}$=20 GeV)
(iii) $H^0_2+\tilde{\chi}^0_1$ ($m_{H^0_2}$=40 GeV)
(iv) $H^0_3+\tilde{\chi}^0_1$ ($m_{H^0_2}$=40 GeV)

Fig. 4(b)

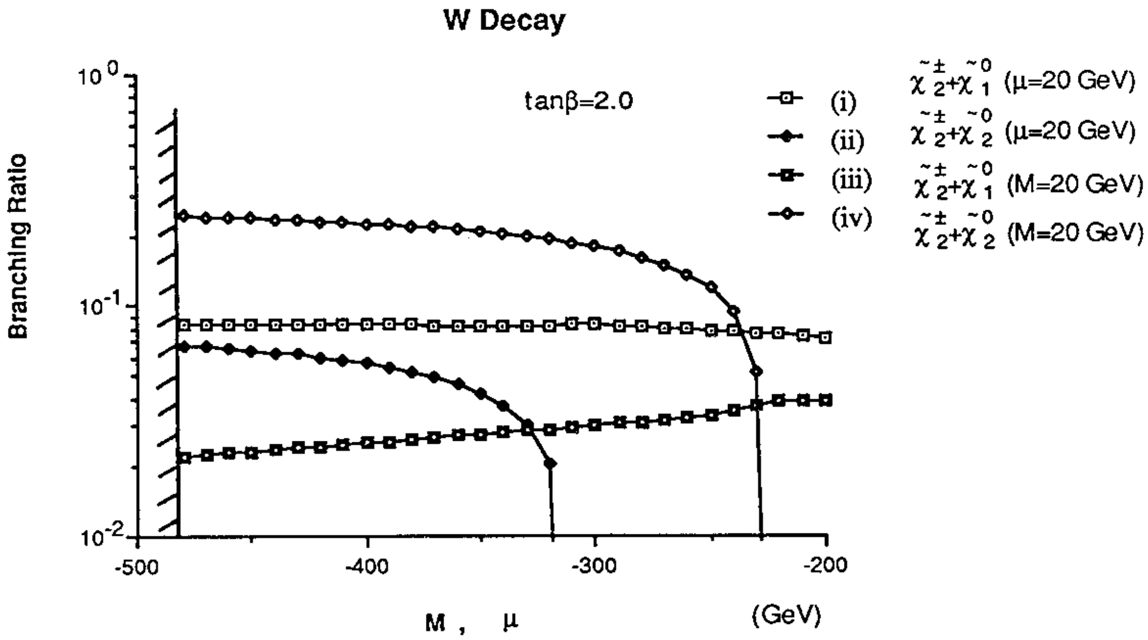

W Decay
tanβ=2.0
Branching Ratio
10^0
10^{-1}
10^{-2}
-500
-400
-300
-200
M , μ
(GeV)
(i) $\tilde{\chi}^{\pm}_2+\tilde{\chi}^0_1$ (μ=20 GeV)
(ii) $\tilde{\chi}^{\pm}_2+\tilde{\chi}^0_2$ (μ=20 GeV)
(iii) $\tilde{\chi}^{\pm}_2+\tilde{\chi}^0_1$ (M=20 GeV)
(iv) $\tilde{\chi}^{\pm}_2+\tilde{\chi}^0_2$ (M=20 GeV)

Fig. 5