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SEARCHES FOR SUPERSYMMETRIC PARTICLES PRODUCED IN Z BOSON DECAY*

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ABSTRACT

We have searched for supersymmetric particles in 528 Z decays with the Mark II detector at SLC. No event passed our supersymmetric event selection criteria. We place 95% confidence level lower mass limits on degenerate squarks, non–degenerate up-type squarks, non-degenerate down-type squarks, charginos, pair–produced unstable neutralinos, and associated–produced neutralinos:

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Supersymmetric theories have great theoretical appeal, but are difficult to test experimentally since there are no model-independent predictions for the masses of the supersymmetric partners of the known fermions and gauge bosons. There is some hope, though, that these masses are less than 1 TeV/c^2 , since supersymmetric theories can naturally accomodate the disparate energy scales of the electroweak interaction (10^2 GeV) and grand unification (10^{14}—10^{17} GeV) if the masses of supersymmetric particles are less than about 1 TeV/c^2 .[1]

-.-We have searched for supersymmetric particles in Z boson decay using data from the Mark II detector at the SLAC e^+e^- Linear Collider (SLC) operating in the e^+e^- center-of-mass energy (E_{cm}) range from 89.2 to 93.0 GeV. Our results cover some gaps in the searches that have been performed at $p\ \bar{p}$ colliders for the scalar partners of quarks, and they extend the mass range of supersymmetric particle limits that have been set at lower energy e^+e^- colliders.

'Our searches are made within the context of the minimal supersymmetric extension to the standard model.' The types of supersymmetric particles, their production cross-section, and their decay are assumed governed by this *model.

Even within the minimal supersymmetric extension to the standard model there are numerous unknown parameters. We assume that the lightest neutralino, $\tilde{\chi}_1^0$, is the lightest supersymmetric particle. We assume R-parity conservation, so that the $\tilde{\chi}_1^0$ is stable and interacts weakly with the material in our detector. We do not consider loop decays or four-body decays of supersymmetric particles. Finally, we assume that unstable supersymmetric particles decay within 1 cm of the collision point.

We specifically search for squarks, charginos and neutralinos. We assume that a squark $\tilde{q}$ decays 100 % via $\tilde{q} \to q\tilde{\chi}_1^0$. A search by the UA1 collaboration[2] has excluded squarks with masses up to 45 GeV/c^2 and the CDF collaboration[3] has excluded squarks with masses up to 74 GeV/c^2 . These searches, however, assume that the u,d,s,c, and b-type squarks ($\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b}$) are degenerate in mass and that the mass of the lightest neutralino, $M_{\tilde{\chi}_1^0}$, is not too large. For example, the UA1 limits are not valid if $M_{\tilde{q}} > 40$ GeV/c^2 and $M_{\tilde{\chi}_1^0} > 20$ GeV/c^2 . Similarly, for squark masses near 70 GeV/c^2 , the CDF limits are not valid if $M_{\tilde{\chi}_1^0} > 30$ GeV/c^2 .

We present our degenerate squark limits as a function of squark mass and $\tilde{\chi}_1^0$ mass, and we exclude regions with $M_{\tilde{q}} - M_{\tilde{\chi}_1^0}$ as small as 3 GeV/c^2 . In addition, we drop the assumption that the udscb squarks are degenerate in mass, and present mass limits for up-type and down-type squarks separately, assuming only that the left and right-handed versions of these squarks are degenerate.

Charginos are the supersymmetric partners of the charged components of Higgs doublets and the W boson. In the minimal supersymmetric extension to the standard model there are two charginos, $\tilde{\chi}_1^+$ and $\tilde{\chi}_2^+$, but only the lighter one, $\tilde{\chi}_1^+$, is allowed to have a mass less than half the Z boson mass. The $\tilde{\chi}_1^+$ is assumed to decay via $\tilde{\chi}_1^+ \rightarrow W^{+*}\tilde{\chi}_1^0$ or $\tilde{\chi}_1^+ \rightarrow H^{+*}\tilde{\chi}_1^0$, where W^{+*} represents a virtual W boson and H^{+*} represents a virtual (or possibly real) charged Higgs boson.

Neutralinos are mixtures of the supersymmetric partners of the photon, the Z boson and the neutral components of Higgs doublets. There are four neutralinos in the minimal supersymmetric extension to the standard model: $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$. The numbering orders the masses of the neutralinos, 1 being the lightest. The $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ can have masses less than half the Z boson mass, while the $\tilde{\chi}_3^0$ and $\tilde{\chi}_4^0$ will always have masses greater than half the Z boson mass. The sum of the masses of the $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$, and of the $\tilde{\chi}_1^0$ and $\tilde{\chi}_3^0$, can be less than the Z boson mass, while the sum of the masses of all other combinations of non-identical neutralinos will always be greater than the Z boson mass. We present limits on the pair-production of $\tilde{\chi}_2^0$ -particles, and on the associated-production of $\tilde{\chi}_1^0\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0\tilde{\chi}_3^0$. The $\tilde{\chi}_2^0$ is assumed to decay 100% via $\tilde{\chi}_2^0 \rightarrow Z^*\tilde{\chi}_1^0$. In our limits for $Z \rightarrow \tilde{\chi}_3^0\tilde{\chi}_1^0$ we assume that the $\tilde{\chi}_3^0$ decays 100% via $\tilde{\chi}_3^0 \rightarrow Z^*\tilde{\chi}_1^0$.

Details of the Mark II detector can be found elsewhere.[4] A cylindrical drift chamber in a 4.75 kG axial magnetic field measures charged particle momenta. Photons are detected in electromagnetic calorimeters covering the angular region $|\cos\theta| < 0.96$, where θ is the angle with respect to the beam axis. Barrel lead-liquid-argon sampling calorimeters cover the central region $|\cos\theta| < 0.72$ and the remaining solid angle is covered by end-cap lead-proportional-tube calorimeters. The detector is triggered by two or more charged tracks within $|\cos\theta| < 0.76$ or by neutral-energy requirements of a single shower depositing at least 3.3 GeV in the barrel calorimeter or 2.2 GeV in an end-cap calorimeter. This combination results in an estimated trigger efficiency of greater than 99% for hadronic Z decays.

Charged tracks are required to project into a cylindrical volume of radius 1 cm and half-length of 3 cm around the nominal collision point parallel to the beam axis, to be within the angular region $|\cos\theta| < 0.85$, and to have transverse momenta with respect to the beam axis of at least 150 MeV/c. An electromagnetic shower is required to have shower energy greater than 1 GeV and $|\cos 6'| < 0.68$ for the-central calorimeter and $0.68 < |\cos\theta| < 0.95$ for the endcap calorimeter. All events are required to contain at least two charged tracks, and the sum of charged particle energy and shower energy (E_{vis}) must be greater than 0.1 E_{cm}. To ensure that the events are well contained within the detector, the polar angle of the thrust axis (θ_{t}) of each event must satisfy the condition $|\cos\theta_{\text{t}}| < 0.7$.

Supersymmetric event candidates are distinguished from conventional Z decays by means of the event acoplanarity angle ϕ_a. Let $\vec{p}_1$ and $\vec{p}_2$ be the vector sums of the momenta of the charged and neutral tracks in event hemispheres 1 and 2 respectively, where the event hemispheres are-defined by the plane perpendicular to the thrust axis. ϕ_a is defined to be $180°$ minus the angle made by the projections of $\vec{p}_1$ and $\vec{p}_2$ onto the plane perpendicular to the beam axis. If an event hemisphere does not contain any tracks then ϕ_a is assigned the value of $180°$. Fig. 1 shows the distribution of ϕ_a for data, for a QCD Monte Carlo, and for a 35 GeV/c^2 down squark. We require that an event have $\phi_a > 40°$ in order to be a supersymmetric event candidate.

There are no events in our data with $\phi_a > 40°$. We use this result to set limits on various supersymmetric particles. The expected number of produced supersymmetric events before cuts is normalized to the total number of hadronic events (N_h) that fulfill the hadronic event selection criteria described in a previous Letter.[5] The expected number of produced supersymmetric events N_x is given by

$$N_x = \frac{N_h \Gamma_x}{\epsilon_q \Gamma_q + \epsilon_x \Gamma_x} \quad ,$$

where Γ_q is the partial width of the Z to u, ***d,*** s, c, and ***b (udscb)*** quarks, $\epsilon_q = 0.953$ is the efficiency for ***udscb*** quarks to pass the hadronic event criteria, Γ_x is the partial width of the Z to the supersymmetric particle in question, and ϵ_x is the efficiency for the supersymmetric events to pass the hadronic event criteria. First order QCD corrections are used when calculating Γ_q[6] and Γ_x.[7] The data sample consists of N_h = 455 events, corresponding to an integrated luminosity of 19.7 nb^{-1}.

The detection efficiencies (ϵ_D) for supersymmetric particles are calculated with a Monte Carlo program which simulates the production and decay of supersymmetric particles according to the minimal supersymmetric extension to the standard model-. Input parameters to the program are, using the notation of Ref. 1, the Majorana mass parameters M, and M', the Higgs superpotential parameter μ, the ratio of Higgs vacuum expectation values $v_1/v_2 = \tan\beta$, and the masses of squarks and sleptons. The values for M, M' and tan β determine the masses and couplings of the charginos and neutralinos in our Monte Carlo program. In order to fragment quarks in hadronic supersymmetric particle decays, we interface our Monte Carlo program to the Lund 6.3 parton shower Monte Carlo program with Lund symmetric fragmentation.[8]

Detection efficiencies for supersymmetric particles are typically 30 to 50 %. Uncertainties in detection efficiency ($\Delta\epsilon_D/\epsilon_D$) from Monte Carlo statistics ($\approx 5\%$), detector simulation and beam backgrounds ($\approx 1\%$), and fragmentation models ($\approx$ 4%) have been calculated. The number of produced events N_x has both a statistical uncertainty from N_h, and a systematic error due to uncertainties in higher order QCD corrections in the calculation of Γ_x if x is a squark.

The total error on the expected number of events is calculated by summing the statistical and systematic errors in quadrature. We calculate our 95 % confidence level mass limits conservatively by defining the expected number of events to be our best estimate for the expected number of events minus the total error for this estimate.

Fig. 2 contains the 95 % confidence level mass limit contours for up-type squarks and down-type squarks, and for the case when $\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, b$ squarks are degenerate in mass. The limits are shown as a function of squark mass and $\tilde{\chi}_1^0$ mass. Given the sensitivity of the UA1[2] and CDF[3] squark limits to non-zero $\tilde{\chi}_1^0$ masses, we estimate that our degenerate squark limit with $M_{\tilde{q}} > 20\ \mathrm{GeV}/c^2$ and

$M_{\tilde{q}} - M_{\tilde{\chi}_1^0} < 20$ GeV$/c^2$ is a new result. The CELLO collaboration[9] has excluded up-type squarks with $M_{\tilde{u}} < 20$ GeV$/c^2$, so that our up-type squark limit region with $M_{\tilde{u}} > 20$ GeV$/c^2$ is a new result. It has not previously been possible to set limits on down-type squarks, since the coupling of $\tilde{d}$ squarks to a virtual photon is very small. The entire region we exclude for down-type squarks is therefore a new result. The limits for the up-type squark are valid for $\tilde{u}$ and $\tilde{c}$ squarks, and the limits for the down-type squark are valid for $\tilde{d}$, $\tilde{s}$, and $\tilde{b}$ squarks.

---The 95 % confidence level limits for charginos are shown in Fig. 3 as a function of chargino mass and $\tilde{\chi}_1^0$ mass. We show contours for the maximum coupling of a chargino to the Z boson, corresponding to a pure wino $(\tilde{W}^+)$, and for the minimum coupling, corresponding to a pure charged Higgsino $(\tilde{H}^+)$. Because the $\tilde{W}^+$ couples so strongly to the Z boson, we are able to exclude winos with masses as large as 45.9 GeV$/c^2$. Similar chargino limits have been set recently by the ALEPH collaboration" and the OPAL collaboration[11] at the LEP e^+e^- storage ring. In contrast to the ALEPH limit, our limit remains valid if the chargino decays predominantly through a real or virtual charged Higgs.

We cannot assume a minimum Z boson coupling when plotting mass limits for neutralinos, since the coupling of the Z boson to neutralinos can vanish. We therefore present 95 % confidence level contours for different values of the magnitude of the coupling of the Z boson to neutralinos. Using the notation of Ref. 1, the -partial width for the decay

$$Z \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0$$

is determined by the complex left and right-handed coupling parameters O''^L_{ij} and O''^R_{ij}. The left and right-handedcouplings are related in general via

$$O''^R_{ij} = -O''^{L*}_{ij} \quad .$$

Writing O''^L_{ij} in the form

$$O''^L_{ij} = |O''^L_{ij}| e^{i\phi}$$

the coupling of the Z boson to $\tilde{\chi}_i^0$ $\tilde{\chi}_j^0$ can be parametrized by two real parameters

$|O''^L_{ij}|$ and ϕ . $|O''^L_{ij}|$ can take on the values $0 \leq |O''^L_{ij}| \leq 0.5$.

For pair-production $(i = j)$ the phase ϕ is 0 . For associated-production the interpretation of ϕ depends on whether or not CP-violation terms are present in the neutralino mass matrix. If CP is conserved then $\phi = 0$ when $\tilde{\chi}^0_i$ and $\tilde{\chi}^0_j$ have the same CP-parity, while $\phi = \pi/2$ when $\tilde{\chi}^0_i$ and $\tilde{\chi}^0_j$ have opposite CP-parity . If CP is violated then ϕ can take on any value. For fixed values of $|O''^L_{ij}|$, $M_{\tilde{\chi}^0_i}$, and $M_{\tilde{\chi}^0_j}$, the maximum and minimum partial widths for $Z \rightarrow \tilde{\chi}^0_i \tilde{\chi}^0_j$, $i \neq$ j, occur for $\phi = \pi/2$ and $\phi = 0$ respectively.

Fig. 4 (a) shows the 95 % confidence level mass limits for associated–produced neutralinos $\tilde{\chi}^0_2 \tilde{\chi}^0_1$ for the case $\phi = \pi/2$. The different contours correspond to different values of $|O''^L_{12}|$. The limit is also valid for $Z \rightarrow \tilde{\chi}^0_3 \tilde{\chi}^0_1$ if $\Gamma(\tilde{\chi}^0_3 \rightarrow Z^* \tilde{\chi}^0_2) \ll \Gamma(\tilde{\chi}^0_3 \rightarrow Z^* \tilde{\chi}^0_1)$. Fig. 4 (b) shows the mass limits for the case $\phi = 0$.

Finally, Fig. 5 contains the mass limits for the pair production of $\tilde{\chi}^0_2$ neutralinos.

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FIGURE CAPTIONS

1) Event acoplanarity ϕ_a for data (circles, with statistical errors), ***udscb*** QCD Monte Carlo (solid line), and a 35 GeV/c^2 down squark (hatched area, normalized to data). The Monte Carlo simulation includes detector and beam background effects.

2) 95% C.L. mass limit contours for up-type squarks and down-type squarks, and for the case when $\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, b$ squarks are degenerate in mass. For all three contours we assume that left and right-handed squarks are degenerate in mass.

3) 95% C.L. mass limits for charginos as a function of chargino mass and $\tilde{\chi}_1^0$ mass. Contours for a pure wino ($\tilde{W}^+$) and a pure charged Higgsino ($\tilde{H}^+$) are shown. The limits are independent of the hadronic branching fraction of the chargino.

4) 95% C.L. mass limits from the associated-production of $\tilde{\chi}_2^0\tilde{\chi}_1^0$ for various values of the coupling parameter $|O''^{L}_{12}|$ (defined in Ref. 1), assuming (a) $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ have opposite CP-parity and (b) $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ have the same CP-parity. If CP is violated then the limit contour for a given value of $|O''^{L}_{12}|$ will lie somewhere between these two extremes. The parameter $|O''^{L}_{12}|$ can take on the values $0 \leq |O''^{L}_{12}| \leq 0.5$ in the minimal supersymmetric extension to the standard model. These limits apply to $\tilde{\chi}_3^0\tilde{\chi}_1^0$ production if the $\tilde{\chi}_3^0$ decays predominantly through $\tilde{\chi}_3^0 \rightarrow Z^*\tilde{\chi}_1^0$; note that in this case $|O''^{L}_{13}|$ should be substituted for $|O''^{L}_{12}|$ in the figure.

5) 95% C.L. mass limits from the pair-production of $\tilde{\chi}_2^0$ neutralinos for various values of the coupling parameter $|O''^{L}_{22}|$. The parameter $|O''^{L}_{22}|$ can take on the values $0 \leq |O''^{L}_{22}| \leq 0.5$ in the minimal supersymmetric extension to the standard model.

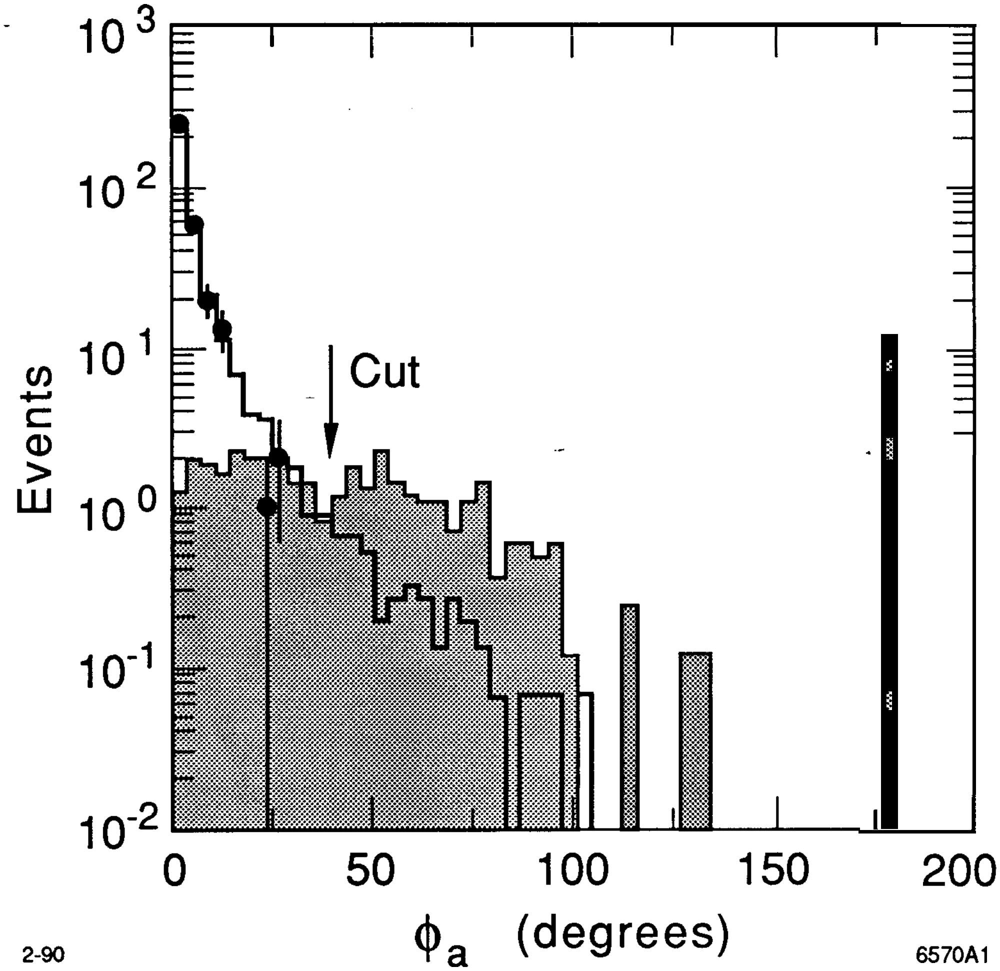


Fig. 1

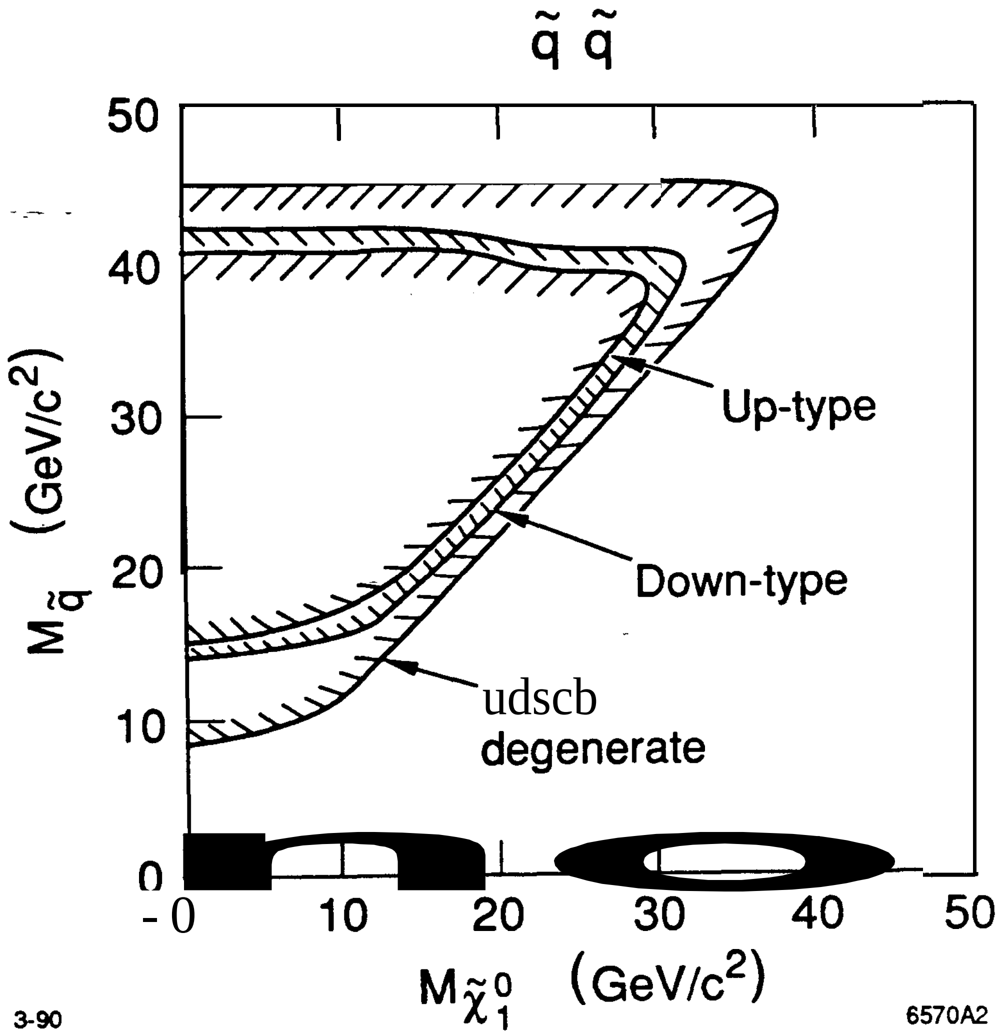
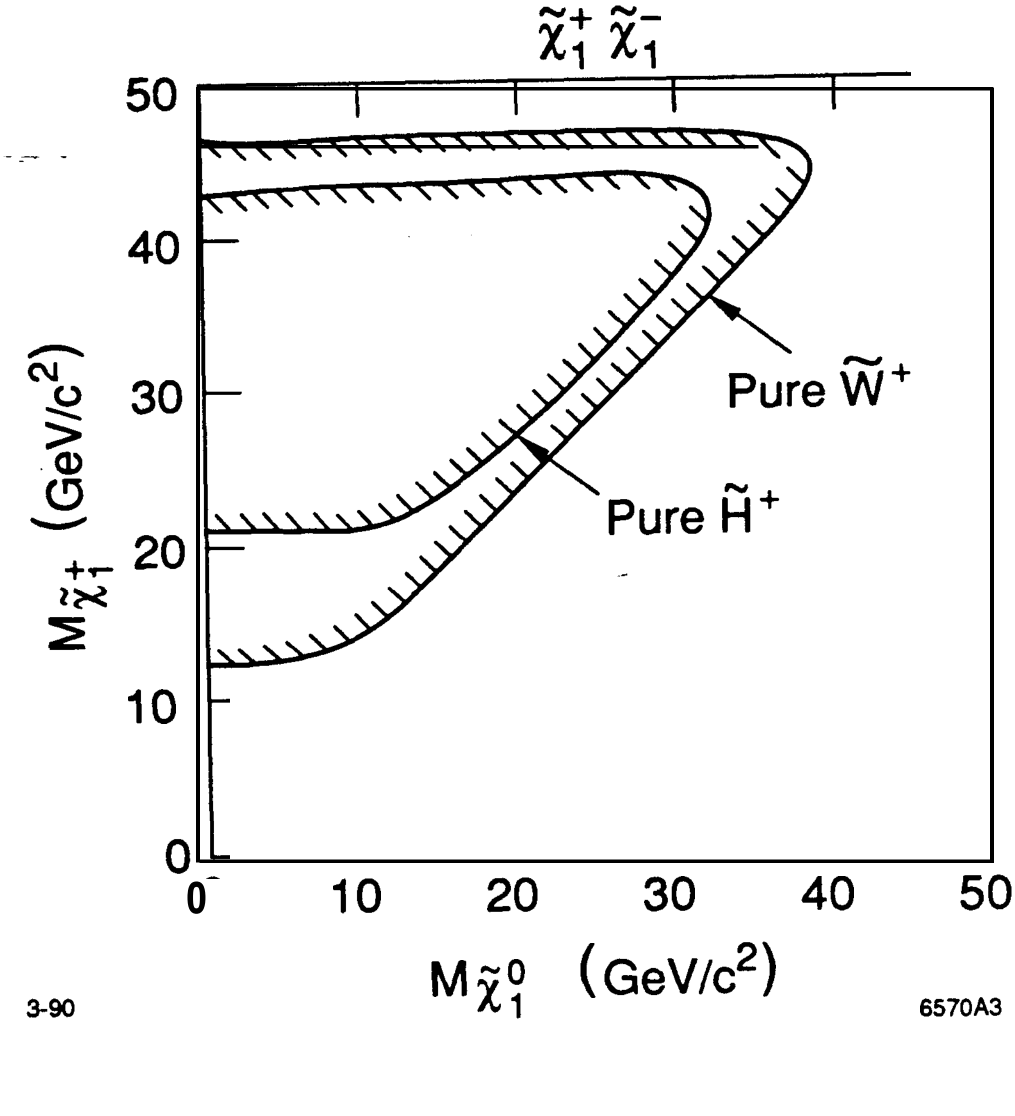
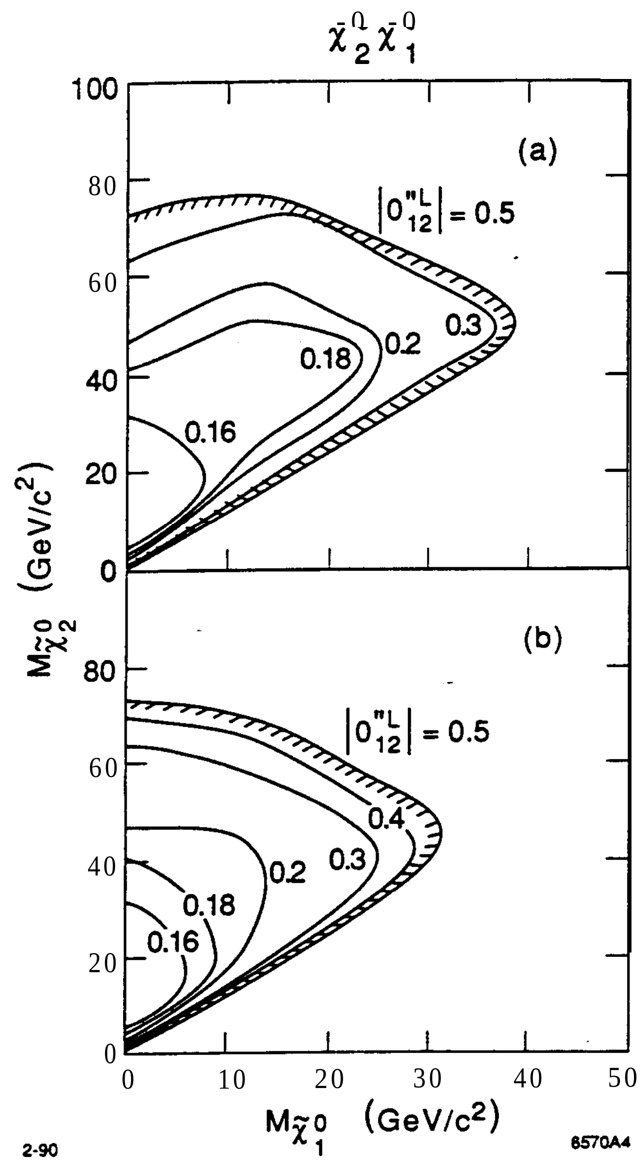

$\tilde{q}\ \bar{\tilde{q}}$
50
40
30
20
10
0
0
10
20
30
40
50
$M_{\tilde{q}}$ (GeV/c^2)
$M_{\tilde{\chi}_1^0}$ (GeV/c^2)
Up-type
Down-type
udscb
degenerate
3-90
6570A2

Fig. 2



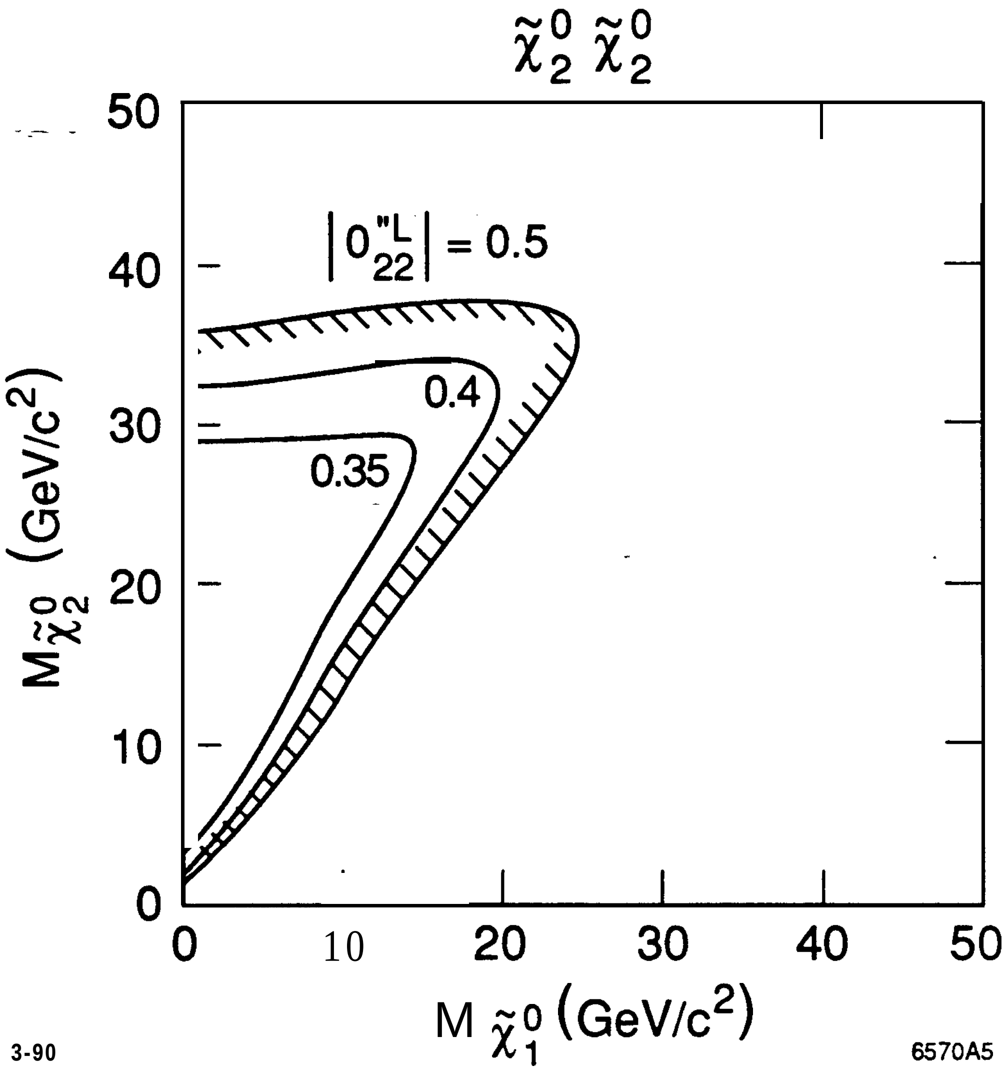
$\tilde{\chi}_1^+ \tilde{\chi}_1^-$
50
40
30
20
10
0
$M_{\tilde{\chi}_1^+}$ (GeV/c^2)
Pure $\tilde{W}^+$
Pure $\tilde{H}^+$
0
10
20
30
40
50
$M_{\tilde{\chi}_1^0}$ (GeV/c^2)
3-90
6570A3

Fig. 3



$\tilde{\chi}_2^0 \tilde{\chi}_1^0$
(a)
$|O''^L_{12}| = 0.5$
0.3
0.2
0.18
0.16
(b)
$|O''^L_{12}| = 0.5$
0.4
0.3
0.2
0.18
0.16
$M_{\tilde{\chi}_2^0}$ (GeV/c²)
$M_{\tilde{\chi}_1^0}$ (GeV/c²)
2-90
6570A4

Fig. 4



$\tilde{\chi}_2^0\ \tilde{\chi}_2^0$
50
40
30
20
10
0
$|O_{22}^{''L}| = 0.5$
0.4
0.35
0
10
20
30
40
50
$M_{\tilde{\chi}_2^0}$ (GeV/c^2)
M $\tilde{\chi}_1^0$ (GeV/c^2)
3-90
6570A5

Fig. 5