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Search for Supersymmetric Particles Using Acoplanar Charged-Particle Pairs from Z^0 Decays

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Abstract

We have performed a search for supersymmetric particles using acoplanar pairs of oppositely-charged particles in decays of the Z^0. In 0.53 pb^{-1} of integrated luminosity near the Z^0 peak, we observe two events where approximately four are expected from background, allowing limits to be extended on combined photino and slepton masses, and also on combined photino and chargino masses.

1 Introduction

Several extensions to the Standard Model [1] of electroweak interactions have been proposed to help explain its shortcomings, two of which are the "naturalness" problem (in which the mass of the Higgs must be fine-tuned to be kept at the electroweak scale) and the related "hierarchy" problem (where the mass of the Higgs boson has large corrections due to any new mass scale) [2]. One way to overcome these problems is to introduce a symmetry between bosons and fermions, known as supersymmetry [3]. If such a symmetry exists then every fermion (boson) would have a bosonic (fermionic) partner. If supersymmetry were unbroken the masses of a particle and its superpartner would be equal. The empirical absence of such equal-mass partners implies that either supersymmetry is badly broken or is not a symmetry of nature.

We describe here a search for Z^0 decays to pairs of oppositely-charged particles which are acoplanar (that is, the plane of the charged particles does not include the beam axis) and which have missing energy. Such decays are a signature of the production of pairs of the supersymmetric partners of the known leptons and pairs of charginos, the superpartners of the $W^{\pm}$ and Higgs bosons [4]. These particles are expected to decay immediately to their associated particles and a photino. The photino is assumed here to be the lightest supersymmetric particle, to be stable (as expected from R-parity conservation [5]), and to interact weakly with matter [6]. Thus it escapes detection, carrying away transverse momentum and energy.

2 Production of Sleptons and Charginos

Figure 1 shows the production processes we consider here and the decay modes of the supersymmetric particles. The production of a pair of supersymmetric scalar leptons (sleptons, denoted as $\tilde{e}$, $\tilde{\mu}$, $\tilde{\tau}$) can occur through the s-channel exchange of a Z^0 or photon, and also through the t-channel exchange of a photino in the case of scalar electron production as shown in Figure 1b. At the Z^0 peak the contribution from the t-channel is less than 10%, and we include it in the result presented here. The cross section depends on the masses of the left- and right-handed sleptons, which may or may not be equal. We present below the limits on these masses for the cases $m_{\tilde{l}_L} = m_{\tilde{l}_R}$

and $m_{\tilde{l}_L} \gg m_{\tilde{l}_R}$, which differ by roughly a factor of two in cross section. As depicted in Figure 1c, the sleptons decay to their associated leptons and a photino.

Pair production of charginos $\tilde{\chi}^{\pm}$, which are the mass eigenstates of admixtures of wino-like and higgsino-like "current" eigenstates, also proceeds through the s-channel as shown in Figure 1a. Though no model-independent prediction for the admixture exists, the couplings of the current eigenstates are predicted exactly. We present below our result for the limiting cases of a pure wino and a pure higgsino; the light chargino in any model will lie between these extremes. The coupling of the wino to the Z^0 is nearly an order of magnitude larger than that of the higgsino [7]. For a pure wino, the cross section at the Z^0 pole is on the order of 10 nb, and decreases slowly with increasing wino mass. In this search we are only sensitive to decay modes resulting in one charged particle per chargino. Such final states arise from from three-body decays to a lepton, its associated neutrino, and a photino (or, more generally, the lightest neutralino [4]) as shown in Figure 1d. We do not consider here the case where the scalar neutrino is lighter than the chargino. For simplicity only decays to electrons and muons in the final state are used to set mass limits; the branching ratios of a chargino to each of these is taken to be 1/9, the minimum of the range given in the model [8].

All the cross section calculations below are made with the assumptions of the minimal supersymmetric standard model [4], [9]. The Born-order cross section is modified strongly by initial-state radiation; at the Z^0 pole the cross section decreases by approximately 30% if the effect is included. We employ here the method of Berends and Kleiss [10] to determine the cross section including this effect.

3 The Apparatus

The ALEPH detector is described elsewhere [11], but we briefly describe here the components relevant to this measurement. The central charged particle tracking detectors are an axial-wire drift chamber (ITC) at small radii and a large cylindrical time projection chamber (TPC). The ITC provides trigger information and up to 8 coordinates in azimuth and radius while the TPC provides up to 21 three-dimensional coordinates along the trajectory of a charged particle. The momentum of charged particles is determined from the curvature of the particle trajectory in the 1.5 Tesla magnetic field from the superconducting solenoid. Between the TPC and the coil cryostat lies the electromagnetic calorimeter (ECAL), which is a lead sheet/proportional wire chamber sandwich having 74000 cathode pad towers in a projective geometry. The 45 wire planes in each of the 36 modules are also read out individually and are used in triggering. At small angles is a similarly-constructed electromagnetic calorimeter, the LCAL, used to measure the luminosity. Finally, the iron return yoke of the solenoid houses the limited streamer tube chambers of the hadronic calorimeter (HCAL), used to measure the energy of hadrons and also to trigger on and identify muons.

Data were collected at seven energies around the Z^0 peak, from 88.3 GeV to 94.3 GeV in steps of 1 GeV, during the first main running period of the LEP machine. Half of the total integrated luminosity of 0.53 pb^{-1} was collected at the energy nearest the peak, 91.3 GeV. A total of 11133 hadronic events (five or more charged tracks carrying at least 10% of the center-of-mass energy) were observed in the sample.

4 Event Selection and Background

Our event selection has two steps, and serves a twofold purpose. Firstly, we wish to select a sample of clean two-track events satisfying basic criteria discussed below. These events can then be compared with our simulation of the well-known Standard Model processes from which they come. Secondly, we wish to apply further criteria to eliminate as many as possible of the coplanar events from these known processes, while maintaining as good efficiency for the acoplanar signal events as possible. The number of events passing our criteria is then used to determine limits on the production of supersymmetric particles.

Our most basic criterion is that there be two and only two tracks from oppositely-charged particles in the tracking detectors. Tracks are required to originate from a point less than 7 cm from the interaction point along the beam axis and less than 3 cm in radius from the beam axis, have an angle of greater than 18.2° with the beam axis, have at least 5 TPC coordinates, and have momentum greater than 100 MeV.

To eliminate events which are acoplanar due to accompanying high-energy photons, events are rejected if there are any ECAL energy deposits over 5 GeV which are more than 25.4° away from the tracks' initial directions. Also, to eliminate events with large initial-state radiation at small angles, or two-photon events with high-energy small-angle beam particles, we require that there be no energy deposit of 5 GeV or more in any of the four modules of the luminosity calorimeter.

The 2151 remaining two-track events are almost all due to the processes

$$e^+e^- \rightarrow e^+e^-(\gamma) \tag{1}$$

$$e^+e^- \rightarrow \mu^+\mu^-(\gamma) \tag{2}$$

$$e^+e^- \rightarrow \tau^+\tau^-(\gamma) \tag{3}$$

$$e^+e^- \rightarrow e^+e^-e^+e^- \tag{4}$$

$$e^+e^- \rightarrow e^+e^-\mu^+\mu^- \tag{5}$$

$$e^+e^- \rightarrow e^+e^-\tau^+\tau^- \tag{6}$$

$$e^+e^- \rightarrow e^+e^-(\text{hadrons}) \tag{7}$$

The first three processes are production of lepton pairs from Z^0 decay, and the last four are two-photon processes in which the final-state "beam" $e^\pm$ escape through the holes in the apparatus for the beam pipe. We have simulated production of 1.5 pb^{-1} of each of the above processes [12], including all particle interaction effects (scattering, bremsstrahlung, energy loss, etc.) and the specific geometry of the sensitive and insensitive regions of our detector. The efficiency of the trigger is determined using the data, and incorporated in the simulation. The simulation uses the same event reconstruction program as the real data.

We can compare the events passing our criteria with the simulated events. To determine the normalization we use the number of hadronic events in the runs from which the sample is selected. Figure 2a compares the distribution of the acoplanarity angle for events with both tracks in the barrel region of the detector. The acoplanarity angle is defined as the difference in azimuthal angle of the two tracks. Clearly the events are very coplanar, which is to be expected from dilepton events and from two-photon events with no activity detected in the LCAL from the scattered beam particles. The agreement between data and simulation is very good both in normalization and in shape. Figure 2b shows a comparison of the distribution of the missing energy. The high end is dominated by the two-photon processes, the middle region is dominated by tau-pair decays, and the peak near zero is from μ- and e-pair events. The shape in the peak disagrees with the simulation due to as-yet-uncorrected drift field distortions in the TPC. These distortions, however, do not significantly affect the analysis.

In the second step of our event selection we wish to eliminate events from the background processes, while keeping the signal events. The signal we seek is characterized by two high-energy charged particles which are acoplanar, and missing energy. To eliminate the Standard Model background we require

- momentum of each track > 2 GeV
- $18.2^\circ <$ acoplanarity angle $< 161.8^\circ$
- 10 GeV $<$ missing energy < 80 GeV

The momentum and acoplanarity requirements reduce the number of background events to thirteen, and after the missing energy requirement we are left with two events. The simulation predicts 4.1 ± 0.3 background events; our observation is consistent with this. Thus, following the procedure for setting limits on a Poisson process with background outlined in Ref. [13], we can exclude at the 95% confidence level any signal process for which we would have seen more than 4.2 signal events. This value is used in determination of mass limits below.

5 Mass Limits on Supersymmetric Particles

We now use the result of the previous section to obtain limits on the masses of supersymmetric particles. To estimate our efficiency for signal detection we use the simulation as described in the previous section. The good agreement of the simulation with our data gives us confidence in applying it to an unobserved process. We use all beam energies and corresponding integrated luminosities determined from the number of hadronic events to calculate the number of events which would pass the same criteria as applied to the data.

Figure 3a shows the region of the $m_{\tilde{e}} - m_{\tilde{\gamma}}$ plane excluded by our search to 95% confidence for the two cases $m_{\tilde{e}_L} = m_{\tilde{e}_R}$ and $m_{\tilde{e}_L} \gg m_{\tilde{e}_R}$. In the degenerate-mass case we exclude scalar electrons with mass less than 43.5 GeV and roughly 5 GeV greater than the photino mass for photino masses up to 35 GeV. Previous limits for the degenerate-mass case from the TOPAZ [14] and ASP [15] experiments are shown. The ASP result is a 90% confidence limit.

The production of a pair of smuons proceeds through exactly the same mechanism as selectron-pair production, except that there is no contribution from t-channel processes. Figure 3b shows the excluded mass region, which covers nearly the entire kinematically accessible region; for the degenerate-mass case smuons with mass less than 42.6 GeV and approximately 5 GeV greater than that of the photino are excluded for a photino mass of up to 33 GeV. The result from TOPAZ [14] for the degenerate-mass case is also shown.

Mass limits have also been obtained by L3 [16] for selectrons and smuons, to 40 and 41 GeV respectively at a photino mass of 20 GeV.

For the production of pairs of scalar taus, which also proceeds only through the s-channel, we take advantage of the 85% branching ratio into single charged particles. The efficiency in this channel is lower, however, due to the softer momentum spectrum and the presence of additional photons from π^0's. Hence we obtain a smaller excluded mass region, shown in Figure 3c along with the region excluded by TOPAZ [14]. In the degenerate-mass case we exclude the region of scalar tau mass below 40.4 GeV and about 5 GeV above the photino mass for photino masses up to 15 GeV.

For chargino pairs we arrive at the limits shown in Figure 4, which cover the mass region up to 45.5 GeV in the pure wino case, and to 44.5 GeV in the limit of a pure higgsino, for photino masses of up to 35 and 30 GeV respectively. The result from the TOPAZ [14] experiment at $m_{\tilde{\gamma}} = 0$ GeV excluded a pure wino below 26.9 GeV, and L3 [16] has excluded a wino with mass less than 42 GeV. (Other experiments [15] [17] exclude winos in a similar mass range, under the assumption of a scalar neutrino lighter than the wino.)

6 Conclusions

We have searched over 10^4 decays of the Z^0 for two acoplanar charged particles with missing energy, and find two candidates satisfying our criteria where we expected approximately four from Standard Model background processes. From this observation we have excluded to 95% confidence regions of the scalar lepton-photino mass plane and the chargino-photino mass plane, where the scalar lepton or chargino is several GeV heavier than the photino such that it decays to final states including a photino. For the sleptons $\tilde{e}$, $\tilde{\mu}$, and $\tilde{\tau}$, the high-mass edges of the excluded regions are 43.5 GeV, 42.6 GeV, and 40.4 GeV, respectively, and are roughly independent of photino mass. A pure wino of mass less than 45.5 GeV is excluded, and a pure higgsino with mass less than 44.5 GeV is excluded, both roughly independent of photino mass up to 28 GeV. These results significantly extend the excluded regions in these parameters.

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List of Figures

Figure 1. Processes studied in this search: *a*, pair production of sleptons and charginos from Z^0 exchange; *b*, t-channel production of scalar electrons; *c*, decay of scalar leptons to associated lepton and photino; *d*, three-body decays of charginos.

Figure 2. Comparison of data and simulated distributions: *a*, acoplanarity angle distribution; *b*, missing energy distribution. Here we require that the momentum be greater than 1 GeV, the invariant mass of the two-track system be greater than 2 GeV, and each track have a polar angle in the range 53° to 127°.

Figure 3. Region in combined slepton and photino masses excluded to 95% confidence by this search: *a*, result for scalar electron pair production with previous results from TOPAZ [14] and ASP [15] (the result from ASP is to 90% confidence); *b*, result for scalar muon pair production with previous result from TOPAZ; *c*, result for scalar tau pair production with previous result from TOPAZ.

Figure 4. Region in combined chargino and photino masses excluded to 95% confidence by this search for the extremes of a pure wino and a pure higgsino.

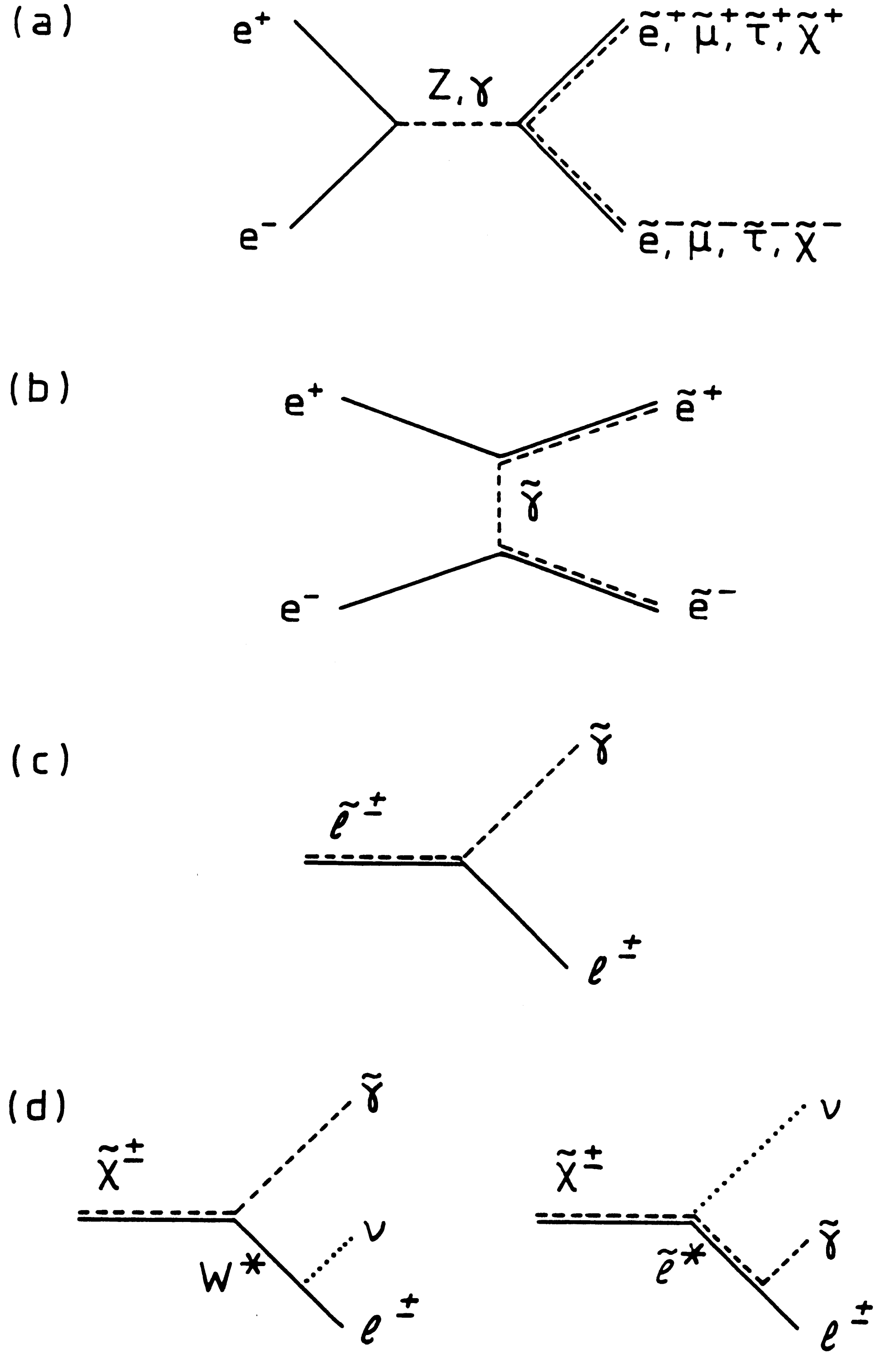


Fig. 1

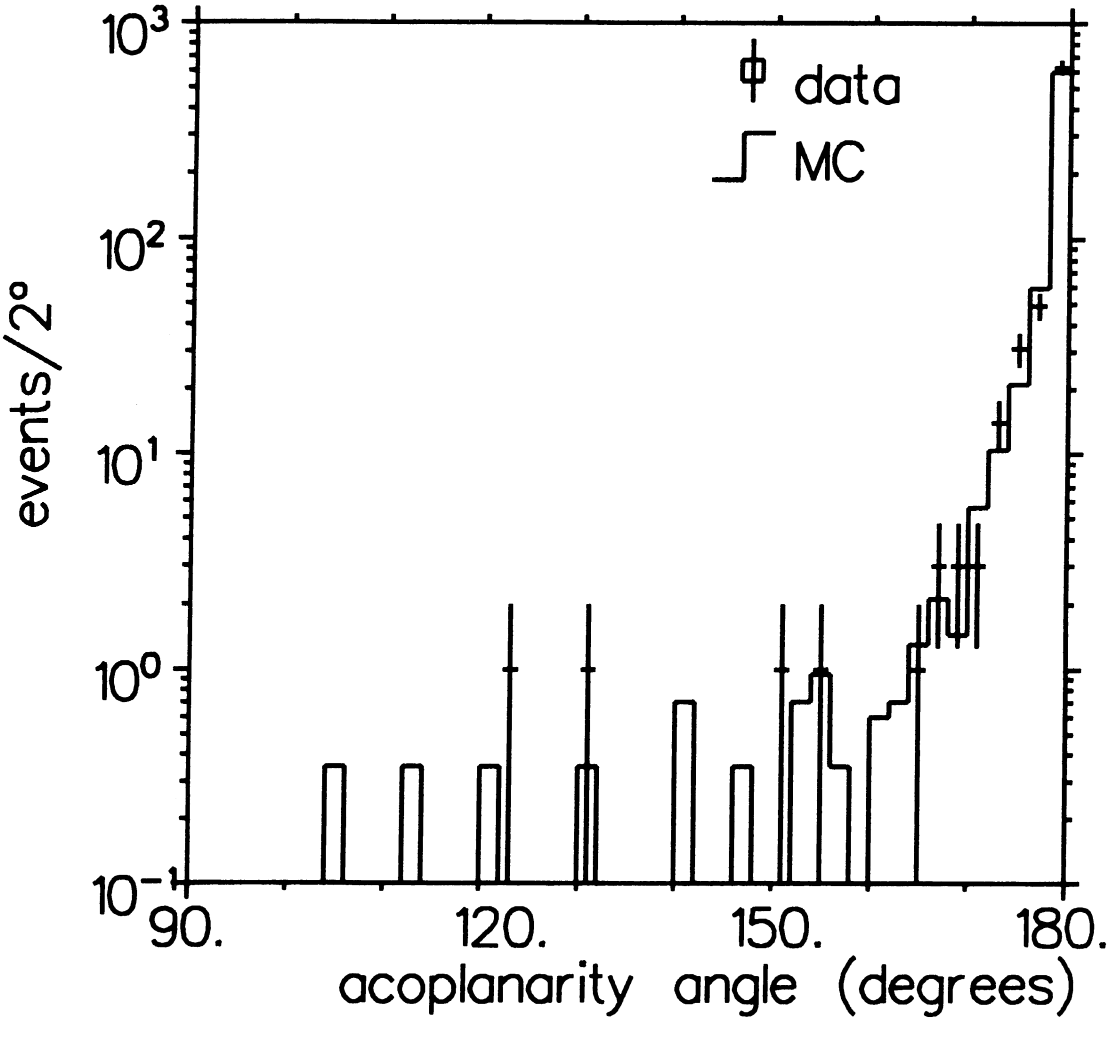

data
MC
events/2°
10³
10²
10¹
10⁰
10⁻¹
90.
120.
150.
180.
acoplanarity angle (degrees)

Fig. 2a

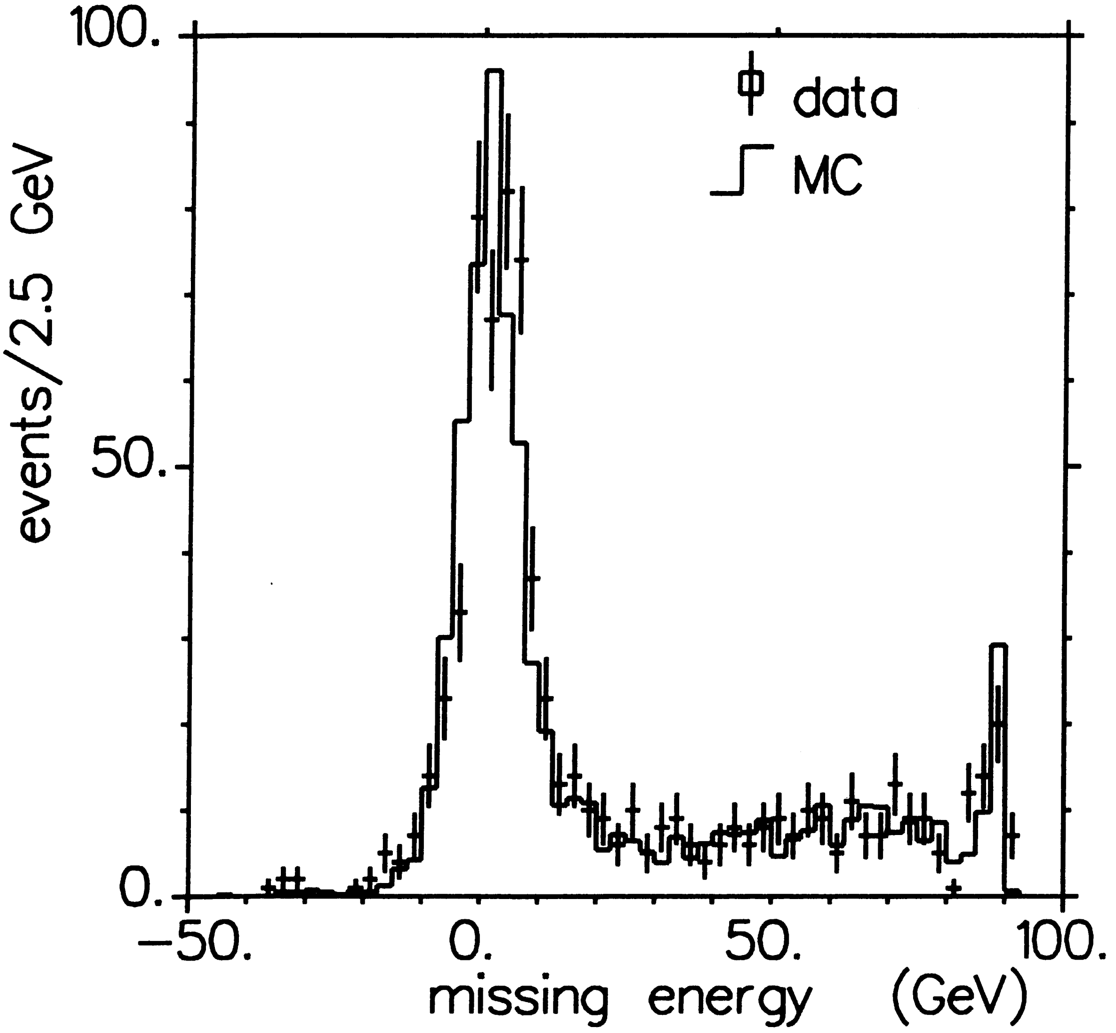
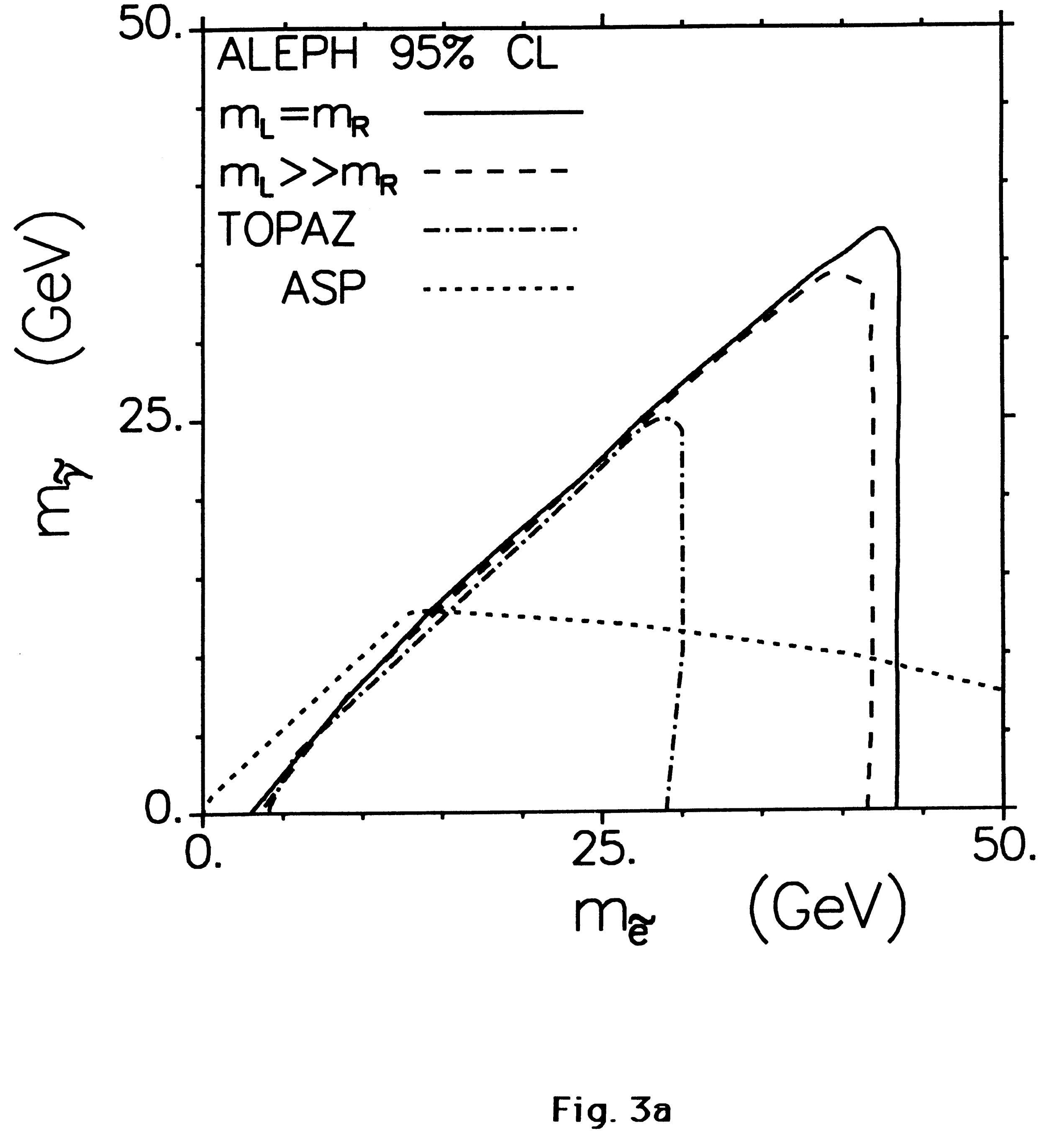


Fig. 2b



50.
25.
0.
0.
25.
50.
ALEPH 95% CL
$m_L = m_R$
$m_L >> m_R$
TOPAZ
ASP
$m_{\tilde{\gamma}}$ (GeV)
$m_{\tilde{e}}$ (GeV)

Fig. 3a

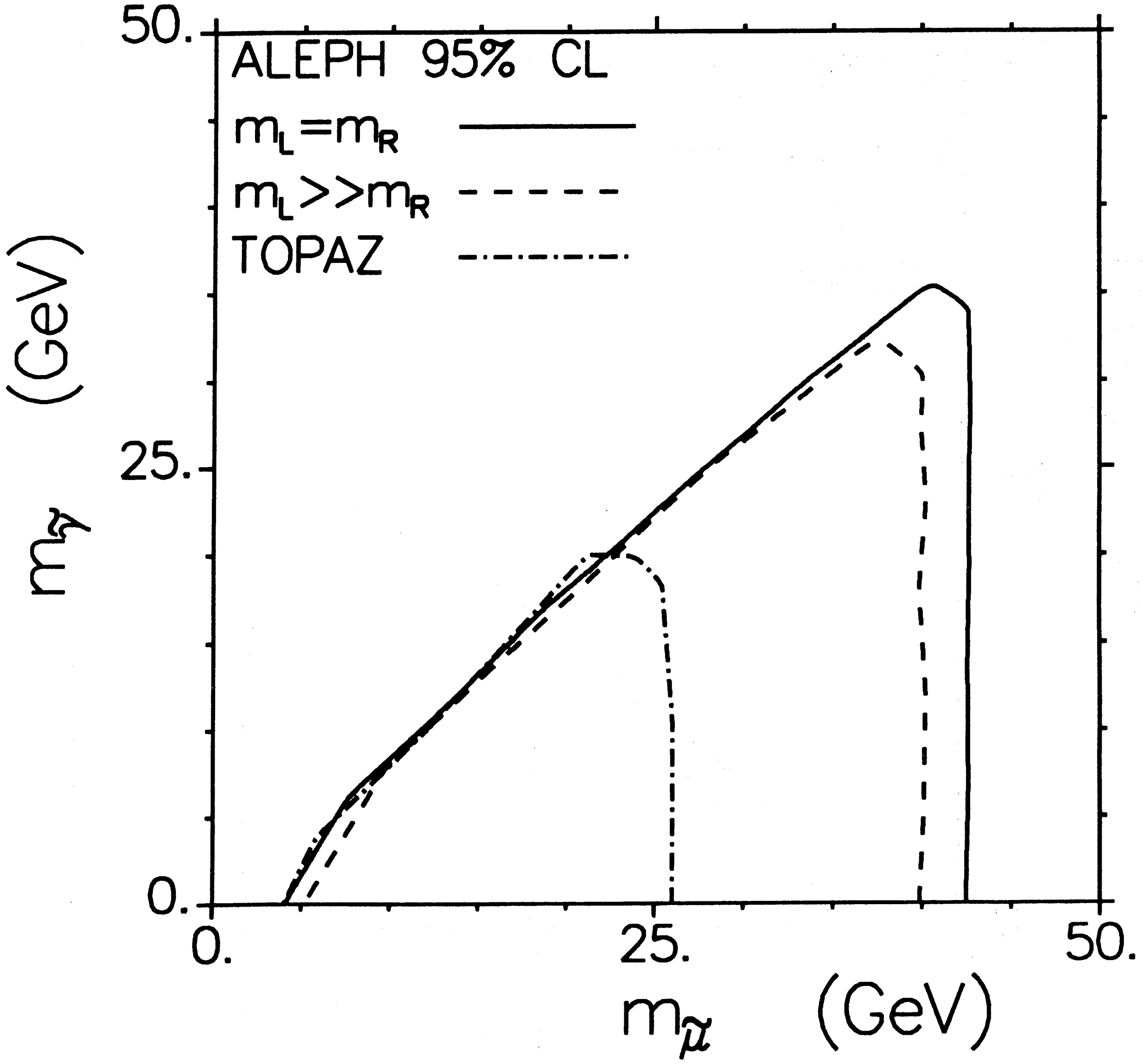

ALEPH 95% CL
$m_L=m_R$
$m_L>>m_R$
TOPAZ
50.
25.
0.
0.
25.
50.
$m_{\tilde{\gamma}}$ (GeV)
$m_{\tilde{\mu}}$ (GeV)

Fig. 3b

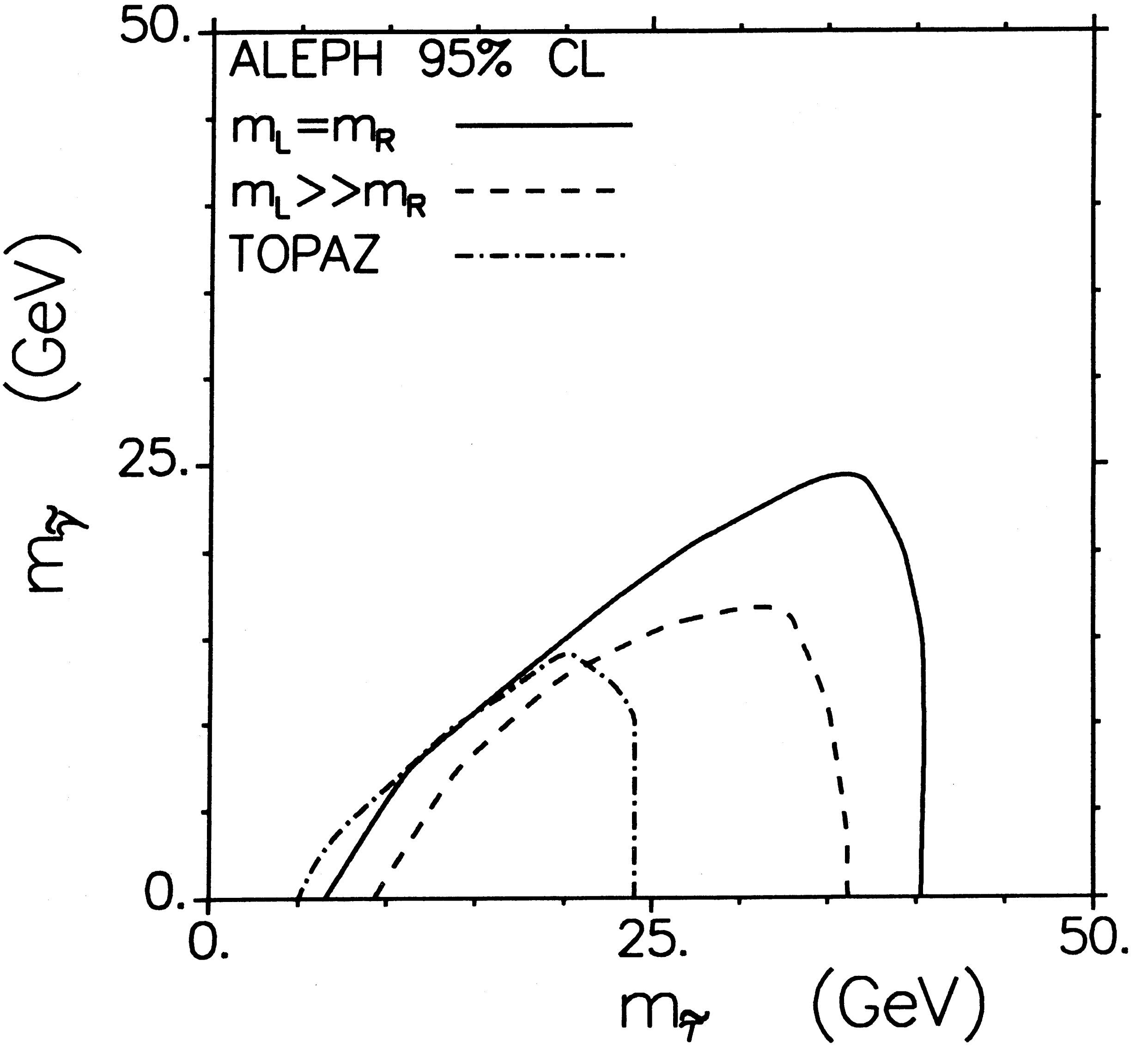

50.
25.
0.
0.
25.
50.
ALEPH 95% CL
$m_L = m_R$
$m_L \gg m_R$
TOPAZ
$m_{\tilde{\gamma}}$ (GeV)
$m_{\tilde{\tau}}$ (GeV)

Fig. 3c

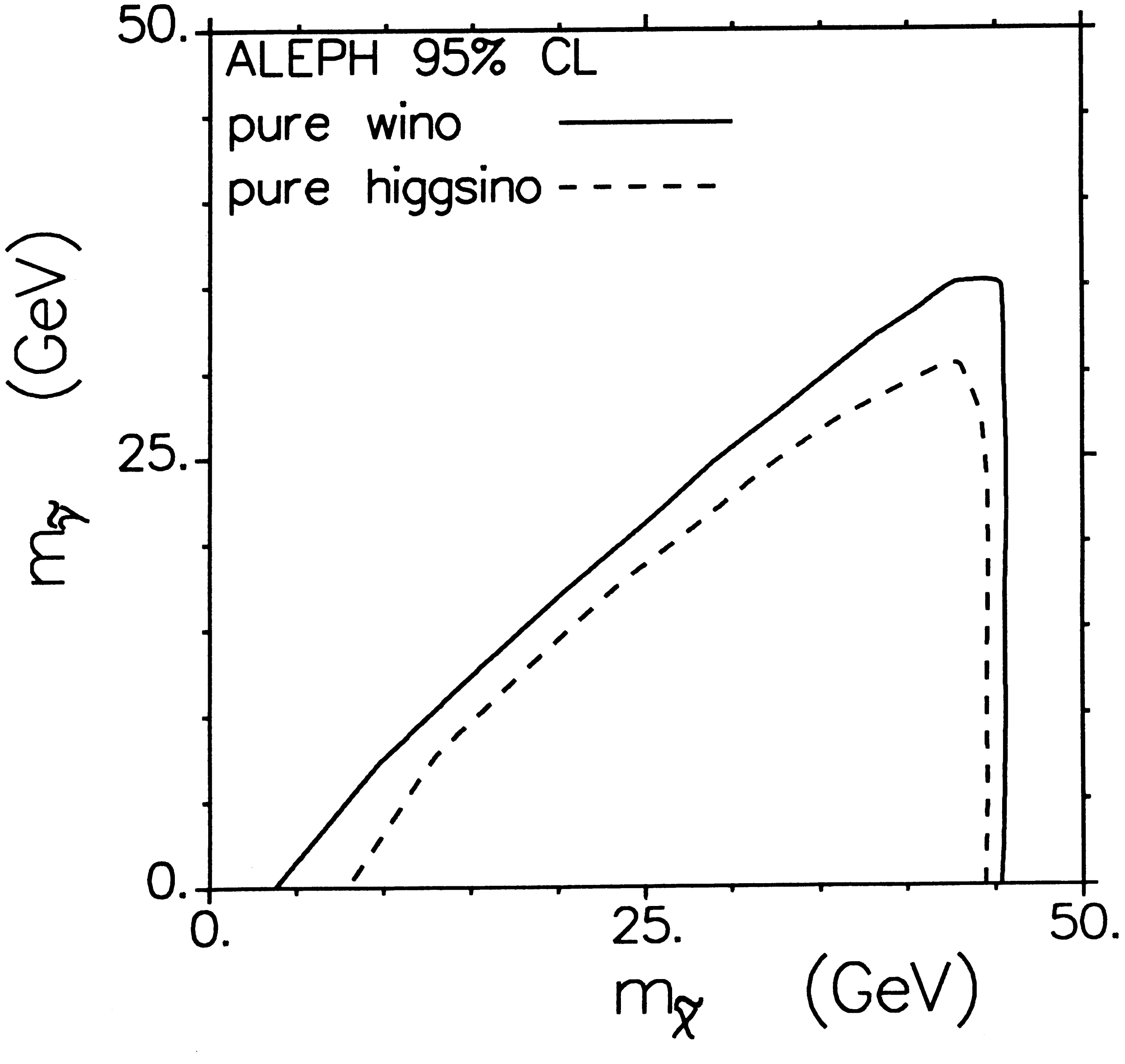

ALEPH 95% CL
pure wino
pure higgsino
50.
25.
0.
0.
25.
50.
$m_{\tilde{\gamma}}$ (GeV)
$m_{\tilde{\chi}}$ (GeV)

Fig. 4