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Abstract

A search has been made for the chargino, the supersymmetric partner of the $W^\pm$ (or the partner of the charged Higgs bosons), in e^+e^- annihilation at PETRA using the JADE detector. The chargino decay modes investigated are $l\tilde{\nu}$, $l\bar{\nu}\tilde{\gamma}$, $q_1\bar{q}_2\tilde{\gamma}$ and $q_1\bar{q}_2\tilde{g}$ (with subsequent gluino decay $\tilde{g} \to q\bar{q}\tilde{\gamma}$). No evidence for such events has been observed. The 95 % C.L. lower limit for the chargino mass is typically 22.5 GeV, depending only slightly on the masses of other supersymmetric particles. If the chargino is stable, the lower mass limit is 21.1 GeV (95 % C.L.).

In supersymmetric theories [1], the partners of the weak vector bosons are spin 1/2 fermions, called the wino $\tilde{W}$ and zino $\tilde{Z}$. In several supersymmetric models [2] the masses of the lightest $\tilde{W}$ and $\tilde{Z}$ are expected to be smaller than those of the $W^{\pm}$ and Z^0, respectively, making a search for them especially promising. The production of neutral supersymmetric gauge fermions (photinos $\tilde{\gamma}$ and zinos $\tilde{Z}$) was investigated by the JADE collaboration in previous analyses [3][4][5]. The charged winos $\tilde{W}$ can, in general, be mixed with the charged higgsinos $\tilde{H}^{\pm}$ [6], the partners of the postulated charged Higgs bosons. The mass eigenstates of these mixtures are called charginos $\tilde{\chi}^{\pm}$. In this paper we report on a search for such chargino states, in e^+e^- annihilation.

In e^+e^- annihilation, the charginos $\tilde{\chi}^{\pm}$ can either be produced singly or in pairs. Pair production proceeds via a virtual photon as for sequential heavy leptons (Fig.1a). In this case the differential cross section for $e^+e^- \rightarrow \tilde{\chi}^+ \tilde{\chi}^-$ is given by

$$d\sigma/d\Omega = (\alpha^2/4s)\cdot\beta(1 + \cos^2\vartheta + (1-\beta^2)\sin^2\vartheta)$$

where β is the velocity of the $\tilde{\chi}^{\pm}$ in the e^+e^- C.M. system and ϑ is the polar angle measured from the e^+ beam direction. A second possibility for pair production is the t-channel $\tilde{\nu}_e$ exchange (Fig.1b). For pure wino production this contributes significantly if the scalar neutrino $\tilde{\nu}_e$ mass is not too large. For higgsino production it is negligible because of the smallness of the Higgs coupling to the light fermions. Since we will give limits for the general case of wino/higgsino mixing, we have not considered the contribution from this diagram. We have checked that the interference between the two processes (Fig.1a and 1b) gives a positive contribution[7]. The single production of $\tilde{\chi}^{\pm}$, together with a scalar neutrino $\tilde{\nu}_e$ and an $e^{\pm}$, (Fig.1c and 1d) is only important for small $\tilde{\nu}_e$ masses [8]. But even for $M(\tilde{\nu}_e) = 0$, its cross section is small if the chargino mass is larger than the beam energy.

Note that charginos can be produced in e^+e^- annihilation even if all the scalar partners of the fermions (scalar leptons $\tilde{l}$, scalar neutrinos $\tilde{\nu}$ and scalar quarks $\tilde{q}$) are very heavy, since the charginos can couple directly to the photon. This is in contrast to the production of neutralinos (photinos, zinos, neutral higgsinos, or mixtures of these) which have a reasonably large cross section only for light scalar electrons ($M(\tilde{e}) \lesssim 100$ GeV at PETRA) [3][4] unless they come from a virtual Z^0 decay [5].

The present analysis has been made with data taken by the JADE detector at PETRA. It is based on an integrated luminosity of 1.5 pb^{-1} at 14 GeV, 2.4 pb^{-1} at 22 GeV, 73.5 pb^{-1} between 27 GeV and 37 GeV, and 25.8 pb^{-1} between 37 GeV and 46.78 GeV, accumulated from summer 1979 to autumn 1984.

Details of the JADE detector and the trigger conditions are described eleswhere [9][10].

There are several possibilities for the decay of the chargino: $\tilde{\chi}^{\pm} \rightarrow q_1\bar{q}_2\tilde{\gamma}$, $\tilde{\chi}^{\pm} \rightarrow l\bar{\nu}\tilde{\gamma}$, $\tilde{\chi}^{\pm} \rightarrow q_1\bar{q}_2\tilde{g}$, and $\tilde{\chi}^{\pm} \rightarrow \tilde{\nu}l$. The branching ratios depend on the relative masses of the chargino, the photino $\tilde{\gamma}$, and the gluino $\tilde{g}$ as well as the masses of scalar quarks and leptons. We have searched for the chargino signal in both the leptonic (electron, muon and tau) as well as in the hadronic final states.

The detection efficiencies were obtained by Monte Carlo. The production and decay processes were simulated according to the differential cross sections and the decay matrix elements. Detector effects were included in the Monte Carlo simulation.

Since the analyses are different for the various $\tilde{\chi}^{\pm}$ decay modes, they will be discussed case by case in the following sections.

(I) Heavy $\tilde{\nu}$ and heavy $\tilde{g}$

If $M(\tilde{\chi}^{\pm}) < M(\tilde{\nu})$ and $M(\tilde{\chi}^{\pm}) < M(\tilde{g})$ (or $M(\tilde{q}) >> M(W^{\pm})$), the only possible decay modes for the chargino are $\tilde{\chi}^{\pm} \rightarrow l\bar{\nu}\tilde{\gamma}$ and $\tilde{\chi}^{\pm} \rightarrow q_1\bar{q}_2\tilde{\gamma}$, where l can be either an electron, muon, or tau lepton. Here $\tilde{\gamma}$ indicates, in general, the lightest neutralino, which escapes undetected. Both of these decays can be mediated either by the exchange of a $W^{\pm}$ boson (Fig.1e and 1f) or by that of scalar leptons or quarks (Fig.1g and 1h). The branching ratios depend strongly on the masses of the scalar leptons and quarks relative to each other as well as to the $W^{\pm}$ mass. Since the masses of the scalar partners are not known, a meaningful investigation implies a search for both the leptonic and the hadronic final states. The branching ratio into leptons and hadrons will be treated as a free parameter. Due to the presence of the $\tilde{\gamma}$ and ν in the final state, a large fraction of the momentum will be unobserved. Hence the characteristic features of these events will be a large acoplanarity and a large missing momentum. The final states we study are (e^+e^- + missing momentum), ($\mu^+\mu^-$ + missing momentum) and ($\tau^+\tau^-$ + missing momentum), where both charginos decay leptonically, as well as (hadrons + missing momentum), where both charginos decay nonleptonically.

(Ia) Leptonic modes

(Ia1) Selection of events with an acoplanar electron pair

The selection criteria for this case are the same as those used in our search for scalar electron pair production [11] and for single zino production where the zino decays into $e^+e^-\tilde{\gamma}$ [4]. Essentially two leadglass clusters associated with a charged track were required with an acoplanarity angle greater than 40 degrees. Full details of the cuts are given in Ref.4. No events remained after these cuts were applied.

(Ia2) Selection of events with an acoplanar muon pair

As in the electron case, the selection criteria for the muon pairs are essentially those used in the search for $\tilde{\mu}^+\tilde{\mu}^-$ pair production [12] and single zino production [4]: The exact cuts can be found in Ref.4. Basically a search was made for events with two muons with an acoplanarity angle between 20 and 150 degrees and a missing momentum larger than 4 GeV. Again no events survived these cuts.

(Ia3) Selection of events with an acoplanar tau pair

If the chargino preferentially couples to heavy particles and if $M(\tilde{l}) < M(\tilde{q})$, $M(W^{\pm})$, it is essential to study the tau decay mode. The search for this mode was made using a sample of 2750 tau pair candidates. For each event, two "taus" were reconstructed using the algorithm given in Ref.13. In addition to the τ selection criteria described elsewhere [13], the acoplanarity angle of the two "tau" momenta with respect to the beam axis was required to be larger than 40 degrees and the scalar sum of charged particle momenta for each "tau" had to be larger than 2 GeV. No events survived this cut.

The matrix element for the decay $\tilde{\chi}^{\pm} \rightarrow l\bar{\nu}\tilde{\gamma}$ mediated by $W^{\pm}$ (Fig.1f) was calculated in analogy to heavy quark decay and the matrix element for the decay mediated by the scalar lepton (Fig.1h) was calculated modifying the zino matrix element calculated by Reiter et al. [14]. Interference between these decay diagrams was not taken into account. Simple three body decay has been used as a third alternative. The detection efficiency was calculated for all three cases and the lowest value was used for the chargino mass limit calculation. For the pair production of $\tilde{\chi}^{\pm}$ where both $\tilde{\chi}^{\pm}$'s decay into $\mu\nu\tilde{\gamma}$, the efficiency, assuming zero photino mass, rises from 6 % at $M(\tilde{\chi}^{\pm})$ = 2 GeV to 30 % at $M(\tilde{\chi}^{\pm})$ = 5 GeV and reaches an asymptotic value of 60 % at $M(\tilde{\chi}^{\pm})$ = 14 GeV. For the decay into electrons the efficiency

is about a factor of three smaller due to the hard cut in the electron energy. The efficiency for the decay into taus is about 4 % at $M(\tilde{\chi}^{\pm})$ = 10 GeV. This small efficiency is due to the small visible energy for the tau modes. The results for Ia1 and Ia2 were combined in order to obtain the $M(\tilde{\chi}^{\pm})$ mass limit. For the $\tilde{\chi}^{\pm} \rightarrow l\bar{\nu}\tilde{\gamma}$ decay modes, we assumed that the couplings of $\tilde{\chi}^{\pm}$ to $\tilde{e}\nu$, $\tilde{\mu}\nu$ and $\tilde{\tau}\nu$ are equal. With the additional assumption that $M(\tilde{e}) \approx M(\tilde{\mu}) \approx M(\tilde{\tau})$, which is expected in many SUSY models, the ratio of branching fractions $Br(e\nu\tilde{\gamma}) : Br(\mu\nu\tilde{\gamma}) : Br(\tau\nu\tilde{\gamma})$ can be derived and the unknown parameter is the total leptonic branching fraction $Br(l\bar{\nu}\tilde{\gamma}) = Br(e\nu\tilde{\gamma}) + Br(\mu\nu\tilde{\gamma}) + Br(\tau\nu\tilde{\gamma})$, which still depends on the mass of scalar quarks. For a fixed chargino mass an upper limit on $Br(l\bar{\nu}\tilde{\gamma})$ can then be calculated from the observed number of acoplanar $\mu^+\mu^-$ and acoplanar e^+e^- candidates, from the production cross section and from the efficiency. The 95 % C.L. contour thus obtained is shown in Figures 2a, 2b and 2c, for the case $M(\tilde{\gamma})$ = 0 GeV, 4 GeV, and 10 GeV, respectively. For the case that $Br(\tau\bar{\nu}\tilde{\gamma}) >> Br(\mu\bar{\nu}\tilde{\gamma}), Br(e\bar{\nu}\tilde{\gamma})$, the limits from the search for acoplanar tau pairs are indicated separately by the dashed curves in Fig.2a, 2b and 2c.

(Ib) Hadronic modes

The event sample used in this analysis is basically the same as that used in the determination of the total cross section [10]. The initial cuts, which were quite loose, essentially required the shower energies in the barrel and endcap leadglass to exceed a certain threshold and the number of charged tracks from the vertex to be larger than four. No cuts on the total visible energy and longitudinal momentum balance were applied at this stage. The exact criteria were cuts (1) to (6) given in Ref.10. More than 50 % of the events are still due to two-photon processes.

(Ib1) Selection of events with acoplanar jets

If both charginos decay like $\tilde{\chi}^{\pm} \rightarrow q\bar{q}\tilde{\gamma}$, the events will be characterized by jets with large acoplanarity. For this reason the criteria chosen were similar to those used in the search for the hadronic decay modes of non-minimal neutral Higgs bosons from virtual Z^0 [5]. Only events with a large acoplanarity angle of the two jets relative to the e^+e^- beam direction were selected. The exact cuts are given in Ref.5 (cuts (B1)-(B4) in that paper). After the cuts one event survived in the sample at $\sqrt{s}$ = 14 GeV and none in the other event samples. As for the leptonic channels, modified heavy quark and zino decay matrix elements were used for the $\tilde{\chi}^{\pm}$ decay. For the fragmentation of the quarks the Lund string model was used [15]. The model parameters had been optimized previously with multihadron data [16]. The application of the Lund model to the process $\tilde{\chi}^{\pm} \rightarrow q_1\bar{q}_2\tilde{\gamma}$ is unique and indicated in Figures 1e and 1g. The detection efficiency obtained is about 4 % for $\beta = 0.8$ and rises to 15 % with β decreasing to 0.4, where β is the velocity of $\tilde{\chi}^{\pm}$ in the e^+e^- C.M. system. The 95 % C.L. upper limits on the hadronic branching ratio $Br(q_1\bar{q}_2\tilde{\gamma})$ were then derived as a function of $\tilde{\chi}^{\pm}$ mass from the number of candidates. These are also given in Figures 2a, 2b and 2c for $M(\tilde{\gamma}) = 0$ GeV, 4 GeV, and 10 GeV, respectively. It is clear from the figures that the investigations of both the leptonic and the hadronic channels are necessary to completely exclude $\tilde{\chi}^{\pm}$ masses up to 22 GeV, independent of the branching ratio.

(Ib2) Limit from the measurement of total hadronic cross section

For chargino decay into a low mass photino the final state is similar to that of ordinary multihadron events unless the missing energy is large. In that case limits on $\tilde{\chi}^{\pm}$ production can be obtained from a precise measurement of the total hadronic cross section. The total hadronic cross section relative to the point-like charged fermion cross section, R, has been measured previously by the JADE collaboration. For C.M. energies in the range from 33.8 to 36.7 GeV the value is 3.99±0.10±0.11 [10], where the first error includes both the statistical and point to point systematic error and the second one is due to the overall normalization. This value is consistent with the standard model prediction. Since in the searches for charginos we investigate deviations from the expectation of the standard model, we have to consider additional uncertainties, namely those from QCD ($\Delta\alpha_s$), from the electroweak theory ($\Delta\sin^2\vartheta_W$) and QED (orders higher than α^3). These are summarized in Table 1. The detection efficiency for the multihadron selection is about 70 % for $M(\tilde{\gamma}) = 0$ and is almost insensitive to the $\tilde{\chi}^{\pm}$ mass up to 23 GeV. For $M(\tilde{\gamma}) = 4$ GeV, the efficiency is about 40 % at $M(\tilde{\chi}^{\pm}) = 10$ GeV, increases with $M(\tilde{\chi}^{\pm})$, and reaches 55 % at $M(\tilde{\chi}^{\pm}) = 15$ GeV. The step in R expected for $\tilde{\chi}^{\pm}$ production from the single photon annihilation diagram is $\Delta R = \beta(3-\beta^2)/2$. By comparing the theoretical prediction, corrected for the detection efficiency and for the hadronic branching fraction, with the experimental 95 % C.L. limit of ΔR, lower limits were set on the chargino mass. In the $M(\tilde{\chi}^{\pm})$-$Br(q_1\bar{q}_2\tilde{\gamma})$ plane the contour of the 95 % C.L. limit is indicated in Fig.1a and 1b by the dashed dotted curve for $M(\tilde{\gamma}) = 0$ and $= 4$ GeV, respectively. For $M(\tilde{\gamma}) = 10$ GeV the detection efficiency for the multihadron cuts is too small to obtain a sensible limit.

(II) $\tilde{\nu}$ heavy , $\tilde{g}$ light

If the gluino is lighter than the chargino and the scalar quark mass is smaller than a few times the $W^{\pm}$ boson mass, the decay mode $\tilde{\chi}^{\pm} \to q_1\bar{q}_2\tilde{g}$, via a virtual scalar quark, is possible(Fig.1i). The gluino $\tilde{g}$ subsequently

decays into $q\bar{q}\tilde{\gamma}$. Note that we are still discussing the case of a heavy $\tilde{\nu}$, such that the decay $\tilde{\chi}^{\pm} \to l\tilde{\nu}$ is not open. Due to the large coupling strength of the strong interaction, the decay into a gluino is then the dominant mode. For scalar quark and lepton masses below 50 GeV its branching ratio is close to 100 % and even for masses up to 150 GeV it is about 60 % [17]. Hence the most likely scenario is that both charginos decay into gluinos. For chargino masses not too close to $\sqrt{s}/2$ the final state is then very similar to that of ordinary multihadron events and mass limits can be obtained from a precise measurement of the total hadronic cross section. Charginos which are produced close to threshold decay almost at rest, and hence the events tend to be more spherical. In that case this signature can be used to distinguish them from ordinary multihadron events.

(II1) Limit from the measurement of total hadronic cross section

The method to obtain the limit by using the total hadronic cross section is just the same as we discussed in (Ib2). The detection efficiency for the decay $\tilde{\chi}^{\pm} \to q_1\bar{q}_2\tilde{g} \to q_1\bar{q}_2 q\bar{q}\tilde{\gamma}$ has been calculated with the Lund model. The two colour singlet strings are stretched between q_1 and $\bar{q}$ as well as between q and $\bar{q}_2$ (Fig.1i). The fragmentation takes place along these strings, similarly to the case of $\tilde{Z} \to q\bar{q}\tilde{g}$. The detection efficiency of pair produced charginos decaying like $\tilde{\chi}^{\pm} \to q_1\bar{q}_2\tilde{g}$ is typically larger than 90 %. At $\sqrt{s} = 40$ GeV, and for $M(\tilde{g}) = 3$ GeV and $M(\tilde{\gamma}) = 0.5$ GeV, it rises from 92 % at $M(\tilde{g}) = 10$ GeV to 98 % at $M(\tilde{\chi}^{\pm}) = 18$ GeV. By comparing the theoretical prediction, corrected for detection efficiency, with the experimental 95 % C.L. limit of ΔR, lower limits were set on the chargino mass. For $M(\tilde{g}) = 3$ GeV and $M(\tilde{\gamma}) = 0.5$ GeV, the lower limit for the chargino mass is 16.5 GeV which is indicated in Fig.3b. This limit is insensitive to the gluino mass. Keeping the ratio $M(\tilde{g})/M(\tilde{\gamma})$ fixed, the limit on the chargino mass changes only by 0.1 GeV if the gluino mass is increased to 10 GeV.

(II2) Selection of spherical hadronic events

As mentioned above, the limit for chargino masses close to the threshold ($M(\tilde{\chi}^{\pm}) \lesssim \sqrt{s}/2$) can be improved by an investigation of spherical events. The selection criteria used, in addition to the basic cuts (1) to (6) of Ref.10, were as follows:

(1) The visible energy of the event E_{vis} was required to satisfy
$$E_{vis} > \sqrt{s}/2$$

(2) The polar angle of the event thrust axis had to satisfy
$$|\cos\vartheta_{th}| < 0.65.$$

(3) The variable S' was required to be large: S' > 0.7, where S' = (3/2)(1-Q'$_3$) with Q'$_3$ being the largest eigenvalue of the modified momentum tensor

$$T_{\alpha\beta}' = (\sum p_{i\alpha} p_{i\beta}/|\vec{p}_i|)/(\sum|\vec{p}_i|), \quad (\alpha,\beta = x,y,z)$$

and the $\vec{p}_i$'s are the momenta of charged and neutral particles.

The modified sphericity S' was empirically found to be more efficient in isolating chargino events than the ordinary sphericity. In Fig.3a the S'-distribution is shown both for the data with $\sqrt{s}$ > 40 GeV as well as the distribution expected by the Lund model in 2nd order QCD. Also indicated is the expectation from chargino pair production where both charginos decay into $q_1\bar{q}_2\tilde{g}$. As observed in the figure, the contribution of the data in the region above S' > 0.7 is small (13 events) and well described by the Lund model (11.3±2.1 events). In contrast to this the distribution from charginos peaks at high S'. To be on the safe side in obtaining limits, these 13 events were nevertheless kept as candidate events and a 95 % C.L. upper limit of 20.7 events was calculated. For M($\tilde{g}$) = 10 GeV and M($\tilde{\gamma}$) = M($\tilde{g}$)/6, the efficiency rises from 10 % at M($\tilde{\chi}^\pm$) = 16 GeV to about 30 % at M($\tilde{\chi}^\pm$) = 22 GeV. In Fig.3b the number of events expected for the above criteria is given as a function of the chargino mass. From the observed number of spherical events the excluded mass region is 13.4 GeV < M($\tilde{\chi}^\pm$) < 22.6 GeV for the case M($\tilde{g}$) = 10 GeV and 15.3 GeV < M($\tilde{\chi}^\pm$) < 22.4 GeV for the case M($\tilde{g}$) = 3 GeV. Also indicated is the lower limit of 16.5 GeV from the measurement of R. The combination of both results excludes masses below 22.4 GeV. Note that this result is insensitive to the error in R, since the overlap of the excluded regions in Fig.3b is substantial.

(III) $\tilde{\nu}$ light

If the masses of the scalar neutrinos $\tilde{\nu}$ are smaller than M($\tilde{\chi}^\pm$), the dominant decay mode is $\tilde{\chi}^\pm \to l\tilde{\nu}$ (see Fig.1j)[1]. In this case the three body decay modes are negligible except when the scalar neutrino mass is close to the chargino mass. It has been checked that in the mass region excluded by the following analysis the Br($l\tilde{\nu}$) is essentially 100 %.

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1 If the scalar lepton $\tilde{l}$ is lighter than the chargino the decay $\tilde{\chi}^\pm \to \tilde{l}\nu$ is, in principle, also possible. However, since we have previously experimentally excluded light $\tilde{l}$'s [11][12], this decay mode is not considered in this analysis.

As before the analysis is based on the pair production of charginos. The visible final state of those reactions is a lepton pair with large acoplanarity due to the missing scalar neutrinos. We limit ourselves to the case where both charginos decay into the same leptons: electron pairs, muon pairs or tau pairs. The selection criteria were identical to those of selection Ia, discussed above. The detection efficiency for those cuts was determined by Monte Carlo simulation. For the 2-μ-signature it varies from 20 % to 50 % for a chargino mass between 10 and 20 GeV, with M($\tilde{\nu}$) = 5 GeV. The corresponding numbers for the 2-electron-signature are 8 % and 40 %. The efficiency decreases rapidly as soon as the $\tilde{\nu}$ mass exceeds 80 % of the chargino mass. We assumed that the coupling of $\tilde{\chi}^\pm$ to $e\tilde{\nu}$, $\mu\tilde{\nu}$ and $\tau\tilde{\nu}$ are equal. From the fact that no candidates were observed for either the e^+e^- or the $\mu^+\mu^-$ case, the excluded region in the M($\tilde{\nu}$)-M($\tilde{\chi}^\pm$) plane with 95 % C.L. was obtained and is shown in Fig.4. Essentially chargino masses up to 22.6 GeV are excluded for small $\tilde{\nu}$ masses (M($\tilde{\nu}$) $\lesssim$ 10 GeV). The limit could not be improved when the limit for the tau mode was combined with the result. If the chargino couples mainly to heavy particles, the decay mode $\tilde{\chi}^\pm \to \tau\tilde{\nu}_\tau$ is dominant. For this case the detection efficiency is about 8 % for M($\tilde{\chi}^\pm$) = 10 GeV and M($\tilde{\nu}_\tau$) = 0. The efficiency is larger than that for the $\tau\bar{\nu}\tilde{\gamma}$ case because of the larger visible energy. For the case of a 100 % decay branching fraction into the $\tau\tilde{\nu}_\tau$ mode the chargino mass limit was obtained as a function of the $\tilde{\nu}_\tau$ mass. The 95 % C.L. limit is indicated by a dashed curve in Fig.4.

We have also investigated the production of a single chargino (Fig.1c and 1d) [8] by searching for events which contain only one electron, which is further required to have a large transverse momentum [11]. The limits obtained from it are, however, fully covered by those obtained from pair production process even for the pure wino case.

(IV) stable $\tilde{\chi}^\pm$

If the $\tilde{\chi}^\pm$ were to be the lightest supersymmetric particle, it would be stable. A search for heavy stable particles was made in a sample of collinear two charged particle events by using the momentum, time-of-flight and dE/dx measurements. We applied the same cuts as those used in our search for the production of stable scalar muons. The cuts are given in that paper [12]. A lower mass limit of 21.1 GeV was obtained for stable charginos. The limit is slightly better than that for stable scalar muons because of the larger cross section and the weaker supression due to the threshold effect.

The production of charginos has been investigated previously only for limited cases. For light scalar neutrinos the decay $\tau \to \tilde{\nu}_\tau \tilde{\nu}_l l$ is possible with an intermediate wino. From an analysis of existing results on the tau lifetime and the momentum spectrum of the final state lepton in tau decay a wino lower mass limit equal to the $W^{\pm}$ mass has been derived [18]. This limit is valid, however, only for scalar neutrino masses less than 0.7 GeV. In e^+e^- annihilations, the MARK-J Collaboration has obtained wino mass limits [19] similar to ours although their analysis is limited to the case of a heavy gluino, and to leptonic final states only.

In summary, no evidence has been found for the pair or single production of the supersymmetric partners of charged weak bosons. All possible decay modes of the chargino were investigated i.e. $\tilde{\chi}^{\pm} \to q_1\bar{q}_2\tilde{\gamma}$, $\tilde{\chi}^{\pm} \to l\bar{\nu}\tilde{\gamma}$, $\tilde{\chi}^{\pm} \to q_1\bar{q}_2\tilde{g}$, and $\tilde{\chi}^{\pm} \to \tilde{\nu}l$. Chargino masses up to ≈22.5 GeV are excluded with 95% C.L., quite independent of the branching ratio into the various final states. Since we have looked for all the possible modes for the chargino decay, we are able to set limits for the chargino masses even if several decay channels are open. For example, if scalar leptons, scalar neutrinos and scalar quarks are heavy (say 300 GeV) and the gluinos are light (say 10 GeV), there are three possible decay modes: $q_1\bar{q}_2\tilde{g}$, $q_1\bar{q}_2\tilde{\gamma}$ and $l\bar{\nu}\tilde{\gamma}$. Since all these modes were searched for, we excluded chargino masses up to approximately 22.5 GeV, independent of the branching fractions. The only case that cannot be detected in our analysis is thus the case of the chargino preferentially decaying into a heavy invisible particle (photino, stable neutral higgsino or scalar neutrino), whose mass is close to the chargino mass. In this case most of the energy would be carried by the invisible particle and the detection efficiency would then be almost zero. For the case of a stable chargino, the 95 % C.L. lower mass limit is 21.1 GeV.

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REFERENCES

1) J. Wess and B. Zumino, Nucl. Phys. B70(1974)39 and Phys. Lett. 49B(1974)52

A. Salam and B. Strathdee, Phys. Rev. D11(1975)1521

P. Fayet and S. Ferrara, Phys. Rep. 32C(1977)249

2) S. Weinberg, Phys. Rev. Lett. 50(1983)387

P. Fayet, LPTENS 83/16 (1983)

3) JADE- Collaboration, W. Bartel et al., Phys. Lett. 139B(1984)327

4) JADE- Collaboration, W. Bartel et al., Phys. Lett. 146B(1984)126

5) JADE- Collaboration, W. Bartel et al., Phys. Lett. 155B(1985)288

6) K. Inoue, A. Kakuto, H. Komatsu and S. Takeshita, Prog. Theor. Phys. 67(1982)1889

J. Ellis and G.G. Ross, Phys. Lett. 117B(1982)397

J. Ellis, J.S. Hagelin, D.V. Nanopoulos and M. Srednicki, Phys. Lett. 127B(1983)233

J. Ellis, J.-M. Frère, J.S. Hagelin, G.L. Kane and S.T. Petcov, Phys. Lett. 132B(1983)436

7) V. Barger, R.W. Robinett, W.Y. Keung and R.J.N. Phillips, et al., Phys. Lett. 131B(1983)372

8) G. Eilam and E. Reya, Phys. Lett. 145B(1984)425

and the erratum, Phys. Lett. 148B(1984)502

9) JADE- Collaboration, W. Bartel et al., Phys. Lett. 88B(1979)171

10) JADE- Collaboration, W. Bartel et al., Phys. Lett. 129B(1983)145

11) JADE- Collaboration, W. Bartel et al., Phys. Lett. 152B(1985)385

12) JADE- Collaboration, W. Bartel et al., Phys. Lett. 152B(1985)392

For the analysis of the muonic channel for C.M. energies below 37 GeV a reduced data sample corresponding to 37 pb^{-1} was used since an efficient trigger for such events has been in operation only since 1982. The total luminosity for the analysis of this channel was 53 pb^{-1} ($\sqrt{s}$ up to 46.78 GeV).

13) JADE- Collaboration, W. Bartel et al., Study on tau production and decay at PETRA energies, in preparation

14) O. Nachtmann and A. Reiter, Univ. Heidelberg, private communication

15) B. Anderson, G. Gustafson and T. Sjöstrand, Phys.Lett. 94B(1980)211

T. Sjöstrand, Computer Phys. Comm. 27(1982)243

16) JADE- Collaboration, W. Bartel et al., Z. Physik 20C(1983)187

17) D.A. Dicus, S. Nandi and X. Tata, Phys. Lett. 129B(1983)451

A.H. Chamseddine, P.Nath and R. Arnowitt, Phys. Lett. 129B(1983)445

B. Grinstein, J. Polchinski and M.B. Wise, Phys. Lett. 130B(1983)285

18) G.L. Kane and W. Rolnick, Nucl. Phys. B232(1984)21

19) Mark J- Collaboration, B. Adeva et al., Phys. Rev. Lett. 53(1984)1806

The single wino production cross section used in that paper is more than a factor two larger than that we used in our analysis (see Ref.8 erratum).

FIGURE CAPTIONS

FIG. 1 Diagrams for chargino production and decay

(a) Chargino pair production via a virtual photon in e^+e^- annihilation
(b) Chargino pair production via the exchange of a scalar neutrino $\tilde{\nu}_e$ in e^+e^- annihilation
(c) and (d) Single chargino production together with a scalar neutrino and an electron
(e) Hadronic decay of chargino into $q_1\bar{q}_2\tilde{\gamma}$ mediated by $W^\pm$
(f) Leptonic decay of chargino into $l\bar{\nu}\tilde{\gamma}$ mediated by $W^\pm$
(g) Hadronic decay of chargino into $q_1\bar{q}_2\tilde{\gamma}$ mediated by a scalar quark $\tilde{q}$
(h) Leptonic decay of chargino into $l\bar{\nu}\tilde{\gamma}$ mediated by a scalar lepton $\tilde{l}$
(i) Hadronic decay of chargino into $q_1\bar{q}_2\tilde{g}$ mediated by a scalar quark $\tilde{q}$ with subsequent decay of the gluino $\tilde{g}$ into $q\bar{q}\tilde{\gamma}$
(j) Leptonic decay of chargino into $l\ \tilde{\nu}$

FIG. 2 Excluded chargino mass as a function of $Br(l\bar{\nu}\tilde{\gamma})$ and $Br(q_1\bar{q}_2\tilde{\gamma})$ with 95% C.L. For the leptonic decay modes, the solid curves indicate the limits obtained assuming $e/\mu/\tau$ universality for the chargino lepton coupling. The dashed curves indicate the limits for $Br(\tau\bar{\nu}\tilde{\gamma}) >> Br(e\bar{\nu}\tilde{\gamma}), Br(\mu\bar{\nu}\tilde{\gamma})$. For hadronic decay modes, the solid curves indicate the limits obtained from searching for events with a large acoplanarity angle and the dashed dotted curves indicate the limits obtained from R-measurement.
(a) for $M(\tilde{\gamma}) = 0$ GeV
(b) for $M(\tilde{\gamma}) = 4$ GeV
(c) for $M(\tilde{\gamma}) = 10$ GeV

FIG. 3 (a) S' distribution for the data with $\sqrt{s} > 40$ GeV after cuts (1)-(2). The data points are shown with full circles. The solid curve indicates the prediction of the Lund model in 2nd order QCD. The shaded histogram is the Monte Carlo prediction for the chargino events with $M(\tilde{\chi}^\pm) = 21$ GeV, $M(\tilde{g}) = 10$ GeV and $M(\tilde{\gamma}) = 1.7$ GeV, normalised to the same luminosity as the data.
(b) Number of $\tilde{\chi}^\pm$ pair events expected, after applying all the cuts, as a function of $M(\tilde{\chi}^\pm)$ at several $\sqrt{s}$ for $M(\tilde{g}) = 3$ GeV and for $M(\tilde{g}) = 10$ GeV. Also the lower mass limit obtained from the R-measurement is indicated.

FIG. 4 Region in the $M(\tilde{\chi}^\pm)$-$M(\tilde{\nu})$ plane excluded with 95% C.L. For the solid curves the chargino coupling constants to $e\tilde{\nu}$, to $\mu\tilde{\nu}$ and to $\tau\tilde{\nu}$ were

assumed to be equal. The dashed curves indicate the limits for $Br(\tau\tilde{\nu}) >> Br(e\tilde{\nu}), Br(\mu\tilde{\nu})$.

TABLE 1

$\sqrt{s}$	33.8-36.7 GeV
R	3.99
statistical and point-to-point-systematic error	0.10
overall normalization error	0.10
QCD $\Delta\alpha_s/\alpha_s = 0.40$	0.09
electro-weak $\sin^2\theta_W = 0.229\pm0.010$	0.05
QED $O(\alpha^4)$	0.08
sum of the uncertainties	0.19
ΔR (95 % C.L.)	0.31

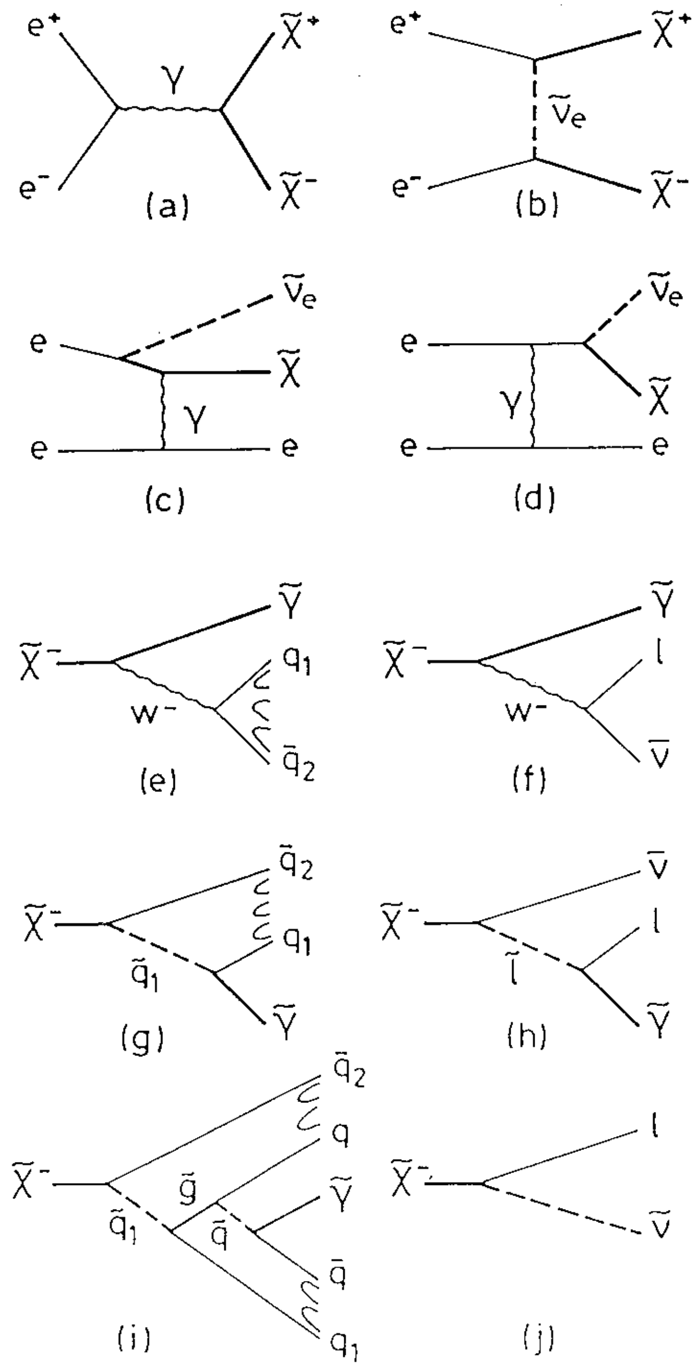

Fig. 1

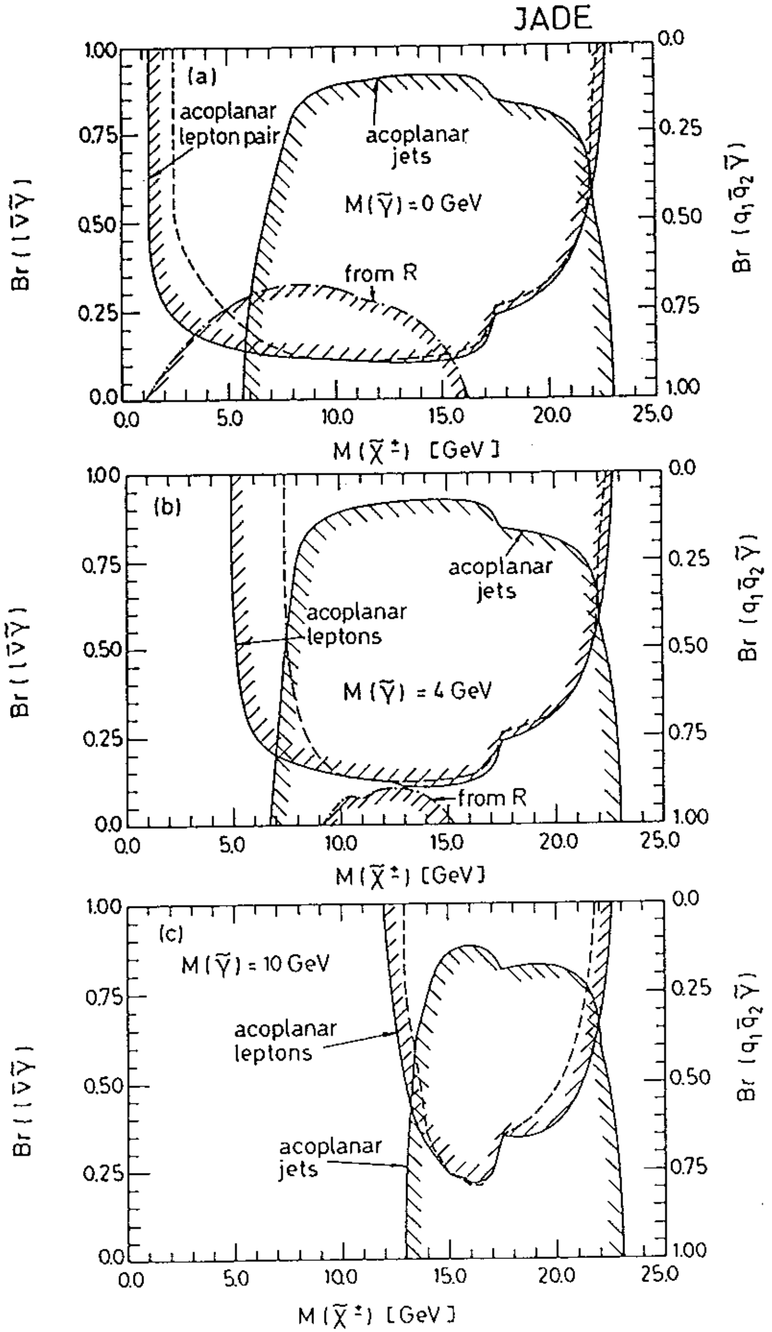
JADE
(a)
acoplanar lepton pair
acoplanar jets
M(γ̃) = 0 GeV
from R
(b)
acoplanar jets
acoplanar leptons
M(γ̃) = 4 GeV
from R
(c)
M(γ̃) = 10 GeV
acoplanar leptons
acoplanar jets
Br (l ν̄ γ̃)
Br (q1 q̄2 γ̃)
M(χ̃±) [GeV]

Fig. 2

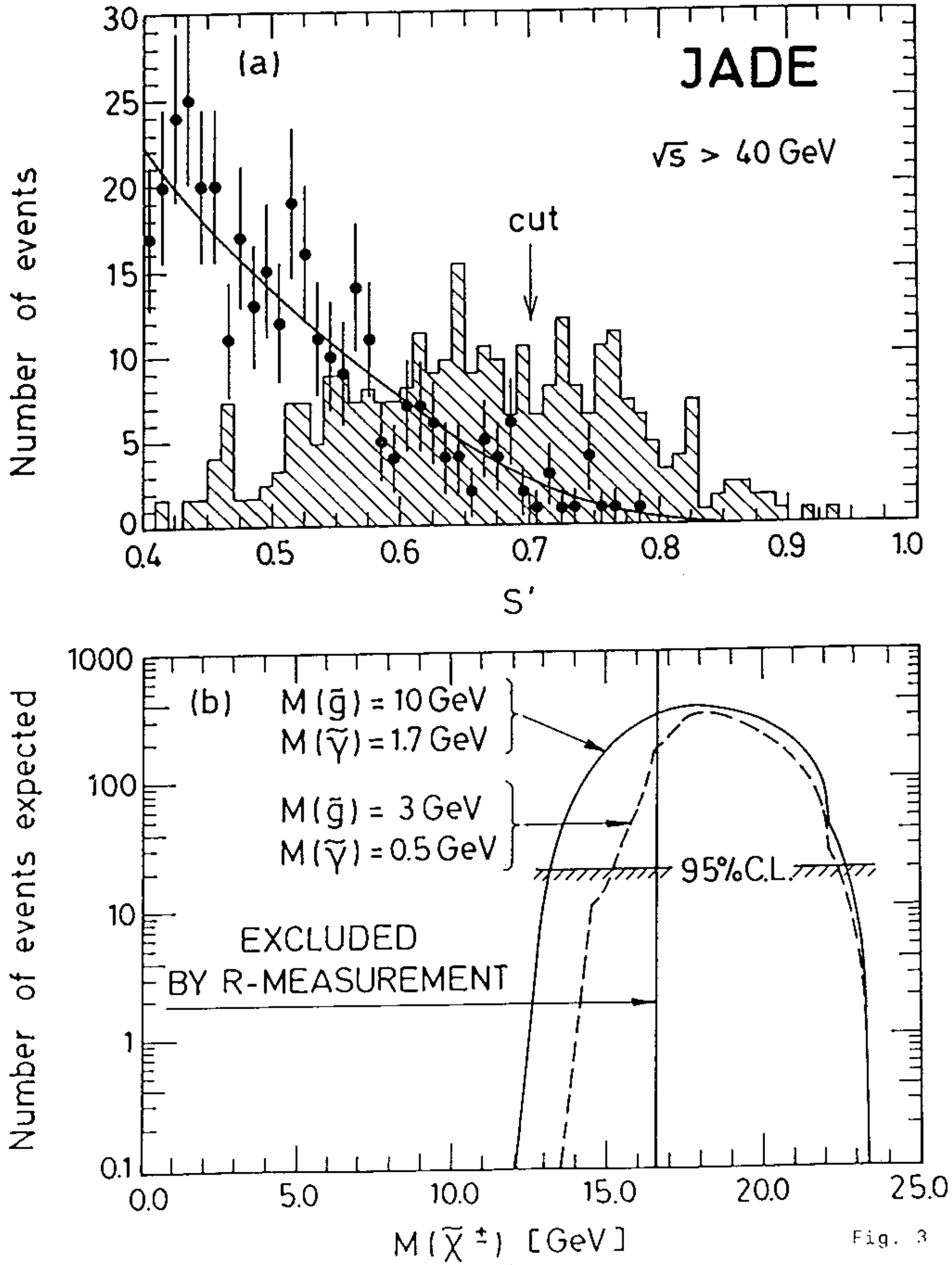
(a)
JADE
√s > 40 GeV
cut
Number of events
S'
(b)
M(g̃) = 10 GeV
M(γ̃) = 1.7 GeV
M(g̃) = 3 GeV
M(γ̃) = 0.5 GeV
95%C.L.
EXCLUDED
BY R-MEASUREMENT
Number of events expected
M(χ̃±) [GeV]

Fig. 3

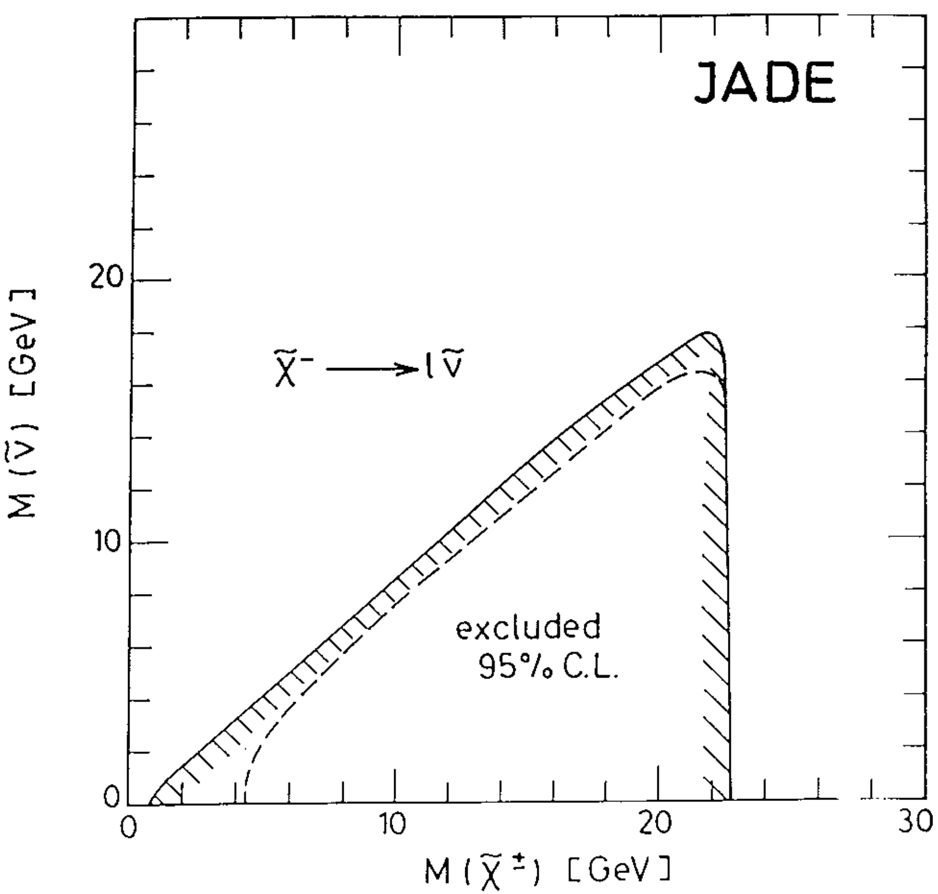
JADE
$\tilde{\chi}^- \longrightarrow l\tilde{\nu}$
excluded
95% C.L.
20
10
0
0
10
20
30
M ($\tilde{\nu}$) [GeV]
M ($\tilde{\chi}^{\pm}$) [GeV]

Fig. 4