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SEARCH FOR SUPERSYMMETRIC PARTICLES AT PEP AND PETRA

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SEARCH FOR SUPERSYMMETRIC PARTICLES AT PEP AND PETRA

CONTENTS

1. INTRODUCTION

Supersymmetry refers to the symmetry between bosons and fermions[1]. The study of supersymmetry has theoretical, but not experimental, motivation, and it is not possible to judge at present whether it will eventually be a useful concept in particle physics[2]. Nevertheless, it is interesting because it introduces a very large number of new particles. In this talk, we give a summary of the recent results from a heroic effort at PEP and PETRA to search for supersymmetry particles.

The Standard Model[3], a gauge theory based on SU(3) x SU(2) x U(1), describes successfully the strong, weak, and electromagnetic interactions. Only the spin-zero Higgs boson, which is needed for spontaneous symmetry breaking in the Standard Model, has not been found so far. As a framework of discussion, we shall therefore use supersymmetric version of the Standard Model[4,5]. More precisely, we shall use N=1 supersymmetry, which means that there is only one set of supersymmetry generators. Thus in N=1 supersymmetry, there is for example just one supersymmetric partner, the wino, $\tilde{W}^{\pm}$, for the $W^{\pm}$ boson of weak interactions. However, in order for the supersymmetric version to be consistent, the Standard Model has to be modified to contain at least two Higgs doublets, leading to five physical Higgs, three neutral and two charged ones (H^+ and H^-). Their supersymmetric partners are called neutral and charged higgsinos. The resulting list of particles is shown in Table 1.

While the supersymmetric version of the Standard Model is not unique, especially concerning supersymmetry breaking, the particle listed in Table 1 are all present. The only possible exception is the Goldstino $\tilde{G}$: in supergravity, the Goldstino is eaten by the spin $\frac{3}{2}$ gravitino (the supersymmetric partner of the graviton) to provide its mass, much in the same way as the charged Higgs in the one - doublet Standard Model is eaten by the W to provide a massive W. The net result is that, in supergravity, the gravitino is produced instead of the Goldstino. The partner of the Goldstino $\tilde{G}$ has properties that depend on the details of the theory and will not be discussed here. In most supersymmetry theories, there is an operator R such that all the usual particles are even under R while the supersymmetric partners are odd, with the consequence that the supersymmetric partner must be produced in pairs. We shall use an additional dotted line to indicate R=-1 particles. If this R- parity is exact, then the lightest particle with R=-1 is stable. It is not known which one of these supersymmetric particles is the lightest; some of the likely candidates are the Goldstino, the photino, and the scalar neutrino.

2. PAIR PRODUCTION OF UNSTABLE PHOTINOS $e^+e^- \rightarrow \tilde{\gamma}\tilde{\gamma}$

As shown in Table 1 the supersymmetric partner of the photon is the photino ($\tilde{\gamma}$) of spin $\frac{1}{2}$. A pair of photinos could be produced in e^+e^- annihilation by the exchange of a scalar electron ($\tilde{e}$) as shown in Fig. 1(a). If the photino is stable, then this process by itself is almost impossible to detect. If the photino is unstable as permitted in some models, then a possible decay mode[6] for this unstable massive photino is $\tilde{\gamma} \rightarrow \tilde{G}\gamma$, as shown in Fig. 1(b).

For the experimental detection of this production of the unstable photino pairs an important quantity is the photino lifetime. If it is too long, then the photino decays occur outside of the detector. The lifetime is given by[6]

$$\tau_{\tilde{\gamma}} = \frac{8\pi\, d^2}{M_{\tilde{\gamma}}^5}$$

where d is an order parameter. Under the assumption that the photinos decay within the detector, the signature is as follows. If the photino is relatively heavy (a few GeV/c^2 or greater) the signature of the event is a pair of acoplanar photons with missing energy as shown in Fig. 1(c). If the photino is light, the signature of the event is a nearly collinear photon pair with relatively low energies (Fig.1(d)).

Fig. 2 gives the excluded region[7] with 95% confidence level in the photino mass and scalar electron mass plane measured by CELLO[8], JADE[9], MARK J[10], and TASSO[11]. It is assumed that the masses of the left-handed and right-handed scalar electrons are the same and $d = (100\ \text{GeV})^2$. The results are not sensitive to the assumed value of d. Changing d only alters the lower limit on the photino mass, a part of the curve which is barely visible in Fig. 2.

3. SEARCH FOR SCALAR ELECTRONS $\tilde{e}^{\pm}$ AND STABLE PHOTINOS $\tilde{\gamma}$

The search[12] for scalar electrons $\tilde{e}$ and stable photinos $\tilde{\gamma}$ has been carried out by ASP[13], MAC[14] and MARK II[15] of PEP and CELLO[16], JADE[17], MARK J[18] and TASSO[19] of PETRA. The following four processes have been used.

A. Pair production of unstable $\tilde{e}^{\pm}$

$$e^+e^- \to \tilde{e}^+ + \tilde{e}^-, \quad \tilde{e}^- \to \tilde{\gamma}e^-, \quad \tilde{e}^+ \to \tilde{\gamma}e^+$$

The diagrams for the production and decay are shown in Fig. 3(a) and (b). The signature of such events is acoplanar e^+e^- pair with missing energies and momenta.

B. Single scalar electron production

$$e^+e^- \to e^{\pm}\,\tilde{e}^{\mp}\,\tilde{\gamma}, \quad \tilde{e}^{\mp} \to e^{\mp}\,\tilde{\gamma}$$

In this process, $\tilde{e}$ is produced by the scattering of an initially radiated photon and an electron as shown in Fig. 3(c). The electron which radiates the photon goes down along the beam pipe and is undetected. The $\tilde{e}$ then decays into a photino and an electron. The signature of this event is a single electron and no other detected particles.

C. Radiative photino pair production

$$e^+e^- \to \gamma\,\tilde{\gamma}\,\tilde{\gamma}$$

The diagrams for this process are given in Fig. 3(d). For stable photinos, the signature for this event is a single photon with nothing else.

D. Pair production of stable $\tilde{e}^{\pm}$

$$e^+e^- \to \tilde{e}^+\,\tilde{e}^-$$

The signature is a collinear heavy muon pair like event.

The experimentally excluded region[12] in the $M_{\tilde{e}} - M_{\tilde{\gamma}}$ plane is shown in Fig. 4. If the photino mass is assumed to be small, the mass limits can be read off from Fig. 4 by the intercept with the $M_{\tilde{e}}$-axis, and the results are shown in Table 2. The best result, 51.1 GeV at 90% confidence level, is obtained by ASP Collaboration using process C.

4. SEARCH FOR SCALAR MUONS $\tilde{\mu}^{\pm}$ AND SCALAR TAUS $\tilde{\tau}^{\pm}$

As shown in Fig. 5, scalar muons are pair produced in e^+e^- annihilation. The differential cross section is

$$\frac{d\sigma}{d\Omega}\,(e^+e^- \to \tilde{\mu}^+\,\tilde{\mu}^-) = \frac{\alpha^2}{8s}\,\beta_{\tilde{\mu}}^3\,\sin^2\theta_{\tilde{\mu}}$$

for $M_{\tilde{\mu}_R}$ and $M_{\tilde{\mu}_L}$ not close to each other. Here s = center of mass energy squared and $\beta_{\tilde{\mu}}$ is the velocity of $\tilde{\mu}$ divided by the velocity of light. For $M_{\tilde{\mu}_R} = M_{\tilde{\mu}_L}$ the above cross-section should be multiplied by 2.

JADE[20] has considered the following cases:

A. $\tilde{\mu} \to \mu\,\tilde{\gamma}$ and $\tilde{\gamma}$ is stable

Here the signature of the event is a pair of acoplanar muons with missing energies and momenta. The excluded region in the $M_{\tilde{\gamma}} - M_{\tilde{\mu}}$ plane with 95% confidence level is given in Fig. 6(a).

B. $\tilde{\mu} \to \mu \tilde{\gamma}$ and $\tilde{\gamma} \to \gamma \tilde{G}$

where $\tilde{G}$ is the massless and stable Goldstino. The signature of the event is $\mu\mu\gamma\gamma$. The excluded region in the $M_{\tilde{\gamma}} - M_{\tilde{\mu}}$ plane with 95% confidence level is given in Fig. 6(b).

Assuming that the photino mass is small, the limits from CELLO[21], JADE[20], MARK J[18], and TASSO[19] are given in Table 2.

Similar searches for the scalar tau have been carried out via $e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$, with the $\tilde{\tau}$ assumed to decay by $\tilde{\tau} \to \tau\tilde{\gamma}$. Thus the $\tilde{\tau}$ mass is taken to be larger than that of τ. The signature of such an event is an isolated e or μ and a hadronic jet. The mass limits are also shown in Table 2.

5. SEARCH FOR ZINOS $\tilde{Z}^o$

Zino $\tilde{Z}^o$, the supersymmetric partner of the Z^o, is produced through the process

$$e^+e^- \to \tilde{Z}^o \tilde{\gamma}$$

by an exchange of a scalar electron $\tilde{e}$ as shown in Fig. 7. The following decay modes of $\tilde{Z}^o$ are explored:

A. $\tilde{Z}^o \to e^+e^-\tilde{\gamma}$, $\mu^+\mu^-\tilde{\gamma}$

as shown in Fig. 8(a). The signature of the event is a pair of acoplanar leptons with missing energies and momenta (Fig. 8(b)).

B. $\tilde{Z}^o \to q\bar{q}\tilde{\gamma}$

as shown in Fig. 9(a). The $\tilde{q}$ in this figure can be real or virtual; thus under B we include (i) $\tilde{Z}^o \to q\bar{q}\tilde{\gamma}$ ($\tilde{q}$ virtual), (ii) $\tilde{Z}^o \to q\bar{\tilde{q}}$ with $\bar{\tilde{q}} \to \bar{q}\tilde{\gamma}$, and (iii) $\tilde{Z}^o \to \tilde{q}\bar{q}$ with $\tilde{q} \to q\tilde{\gamma}$. In all three cases, the detected particles are the same, and the signature is a pair of acoplanar jets (for heavy $\tilde{Z}^o$) or one jet (for light $\tilde{Z}^o$) with missing energies and momenta (Fig. 9(b)).

C. $\tilde{Z}^o \to q\bar{q}\tilde{g}$

as shown in Fig. 10. Similar to case B, the $\tilde{q}$ in this figure can be real or virtual. For light $\tilde{q}$ of mass less than 3 GeV, the branching ratio for this $q\bar{q}\tilde{g}$ is dominant (~99%) due to the strong coupling constant α_s.

Excluded regions in $M_{\tilde{Z}^o} - M_{\tilde{e}}$ plane are shown in Fig. 11 and Fig. 12 from results by CELLO[24], JADE[25], and MARK J[26].

It may be appropriate at this point to add the following remark. It is seen from Table 1 that $\tilde{G}$, $\tilde{\gamma}$, $\tilde{Z}^o$ and $\tilde{H}^o$ all have the same quantum numbers (charge 0, spin $\frac{1}{2}$, color singlet, and R=-1). Thus they can mix, i.e., the physical states of definite masses are a mixture of them. These physical states are referred to as neutralinos. The amount of mixing depends on the nature of supersymmetry breaking, and at present there is no way of choosing among the many possibilities. Strictly speaking, this section should be entitled the search for neutralinos through the production of $\tilde{Z}^o$. Since at least one neutralino must have a large $\tilde{Z}^o$ component, this mixing has only relatively minor effects on the results of Fig. 11 and Fig. 12, provided that the assumptions are fulfilled.

6. SEARCH FOR CHARGINOS $\tilde{\chi}^{\pm}$

Similar to the mixing of the neutral supersymmetric particles just discussed, the wino $\tilde{W}^{\pm}$ and the charged higgsino $\tilde{H}^{\pm}$ of Table 1 also have the same quantum numbers and hence can mix to produce the mass eigenstates called charginos $\tilde{\chi}^{\pm}$. The pair production of $\tilde{\chi}^{\pm}$

$$e^+e^- \to \tilde{\chi}^+ \tilde{\chi}^-$$

can proceed via a virtual photon or a heavy scalar neutrino $\tilde{\nu}_e$ exchange as shown in Fig. 13. Depending on the masses of the supersymmetric particles the charginos can have different dominant decay modes. At PETRA the charginos have been searched through the following modes: (We write down only the ones for χ^-; those for χ^+ are given by charge conjugation.)

A. $\tilde{\chi}^- \to \ell^- \tilde{\nu}_\ell$
as shown in Fig. 14(a), where ℓ = e, μ, or τ. If both $\tilde{\chi}^+$ and $\tilde{\chi}^-$ decay this way, the signature of the event is a pair of acoplanar leptons with missing energies and missing momenta.

B. $\tilde{\chi}^- \to q_1\bar{q}_2\tilde{g}$ (Fig. 14(b))
$\quad\quad\quad\quad \hookrightarrow q\bar{q}\,\tilde{\gamma}$

C. $\tilde{\chi}^- \to q_1\bar{q}_2\,\tilde{\gamma}$ (Fig. 14(c))

D. $\tilde{\chi}^- \to \ell^-\,\bar{\nu}_\ell\,\tilde{\gamma}$
as shown in Fig. 14(d). The signature is the same as A.

E. Stable $\tilde{\chi}^-$. Such event will look like collinear heavy muon pairs.

CELLO[24)], JADE[27)], and MARK J[26)] have searched for the chargino through A, and the excluded region in the $M_{\tilde{\chi}^\pm} - M_{\tilde{\nu}}$ plane is shown in Fig. 15. In addition, JADE[27)] has searched for the chargino through the processes B, C, D, and E, and also through the precise measurement of $R = \dfrac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$. Their result from B and R is that $M_{\tilde{\chi}^\pm}$ cannot be below 22.4 GeV, and from E not below 21.1 GeV. The results from C and D, parametrized by the branching ratio $Br(\ell\tilde{\nu}\tilde{\gamma})$ and $Br(q_1\bar{q}_2\tilde{\gamma})$, are shown in Fig. 16.

Another way to search for the chargino $\tilde{\chi}^\pm$ is to make use of the $\tilde{W}\,e\,\tilde{\nu}$ coupling. Similar to the process $e^+e^- \to \gamma\tilde{\gamma}\tilde{\gamma}$ discussed in Section 3, there is the radiative pair production of scalar neutrinos

$$e^+e^- \to \gamma\tilde{\nu}\bar{\tilde{\nu}}.$$

Assuming the scalar neutrinos do not interact or decay in the detector the ASP data[13)] give a bound on the wino mass $M_{\tilde{W}}$. Using the model of Ref. 28 and with small $M_{\tilde{\nu}}$, the result[13)] is $M_{\tilde{W}} > 48$ GeV/c^2 (90% C.L.).

7. CONCLUSION

Due to the efforts of many physicists working at PEP and PETRA, we have now a great deal of information on the bound on masses of particles expected on the basis of supersymmetry. No such particle, however, has been found. Since a possible reason is that the energy is not high enough, the searches will be continued at other accelerators, including SLC, LEP, HERA, AND $p\bar{p}$ colliders. We eagerly wait for the first discovery of such particles; if and when this happens, it will be a major event for particle physics.

8. ACKNOWLEDGMMENTS

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10. TABLES AND FIGURES

Table 1: List of Particles in N=1 Supersymmetric Standard Model

Spin 0	Spin $\frac{1}{2}$	Spin 1
	Goldstino $\tilde{G}$	
	photino $\tilde{\gamma}$	photon γ
scalar neutrino $\tilde{\nu}$	neutrino ν	
	gluino $\tilde{g}$	gluon g
scalar leptons $\tilde{\ell}_R, \tilde{\ell}_L$	lepton ℓ	
scalar quarks $\tilde{q}_R, \tilde{q}_L$	quark q	
	wino $\tilde{W}^{\pm}$	charged intermediate boson $W^{\pm}$
	zino $\tilde{Z}^{o}$	neutral intermediate boson Z^{o}
neutral Higgs H^{o}	neutral higgsino $\tilde{H}^{o}$	
charged Higgs $H^{\pm}$	charged higgsino $\tilde{H}^{\pm}$	

Table 2: Excluded mass regions in GeV/c^2 for scalar leptons. The photino mass is assumed to be zero.

	$M_{\tilde{e}}$ (GeV/c^2)	$M_{\tilde{\mu}}$ (GeV/c^2)	$M_{\tilde{\tau}}$ (GeV/c^2)
ASP (90% C.L.)	<51 (ref.13)		
ASP (95% C.L.)	<44 (ref.13)		
CELLO (95% C.L.)	<25 (ref.16)	<3.3 to 16 (ref. 21)	M_τ to 3.8 6 to 15.3 } (ref.21)
JADE (95% C.L.)	<25 (ref.17)	<20.3 (ref.20)	M_τ to 18 (ref.22)
MAC (90% C.L.)	<43.5(ref.14)		
MARK II (95% C.L.)	<22 (ref.15)		M_τ to 9.9 (ref.23)
MARK J (95% C.L.)		<20 (ref.18)	M_τ to 17 (ref.18)
TASSO (95% C.L.)	<16.6(ref.19)	<16.4 (ref.19)	

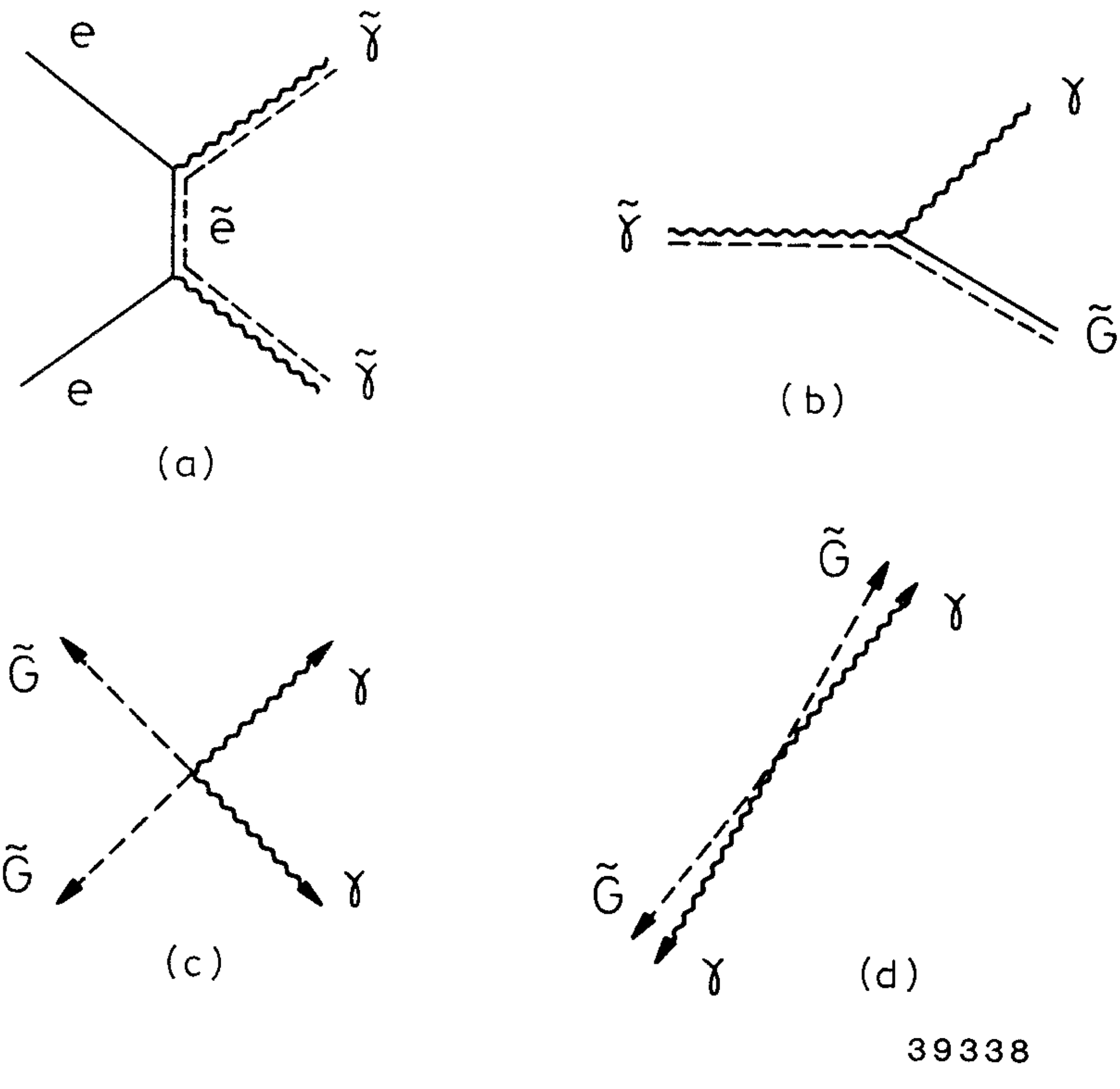

Fig. 1: Search for unstable photinos: this figure gives the Feynman diagrams for production (a) and decay into $\tilde{G}\gamma$ (b), and the schematic diagrams for the event when the photino mass is large (c) or small (d).

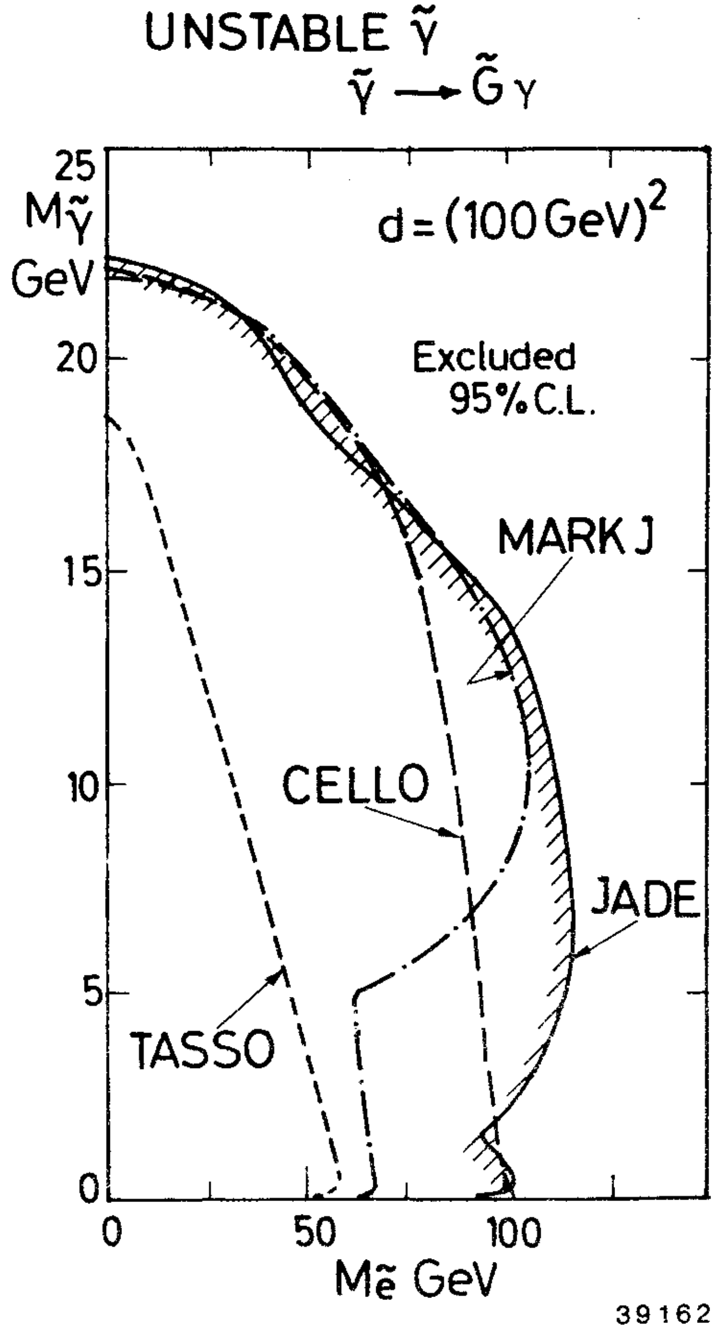

Fig. 2: Excluded region, with 95% confidence level, in $M_{\tilde{\gamma}}$-$M_{\tilde{e}}$ plane for unstable photinos.

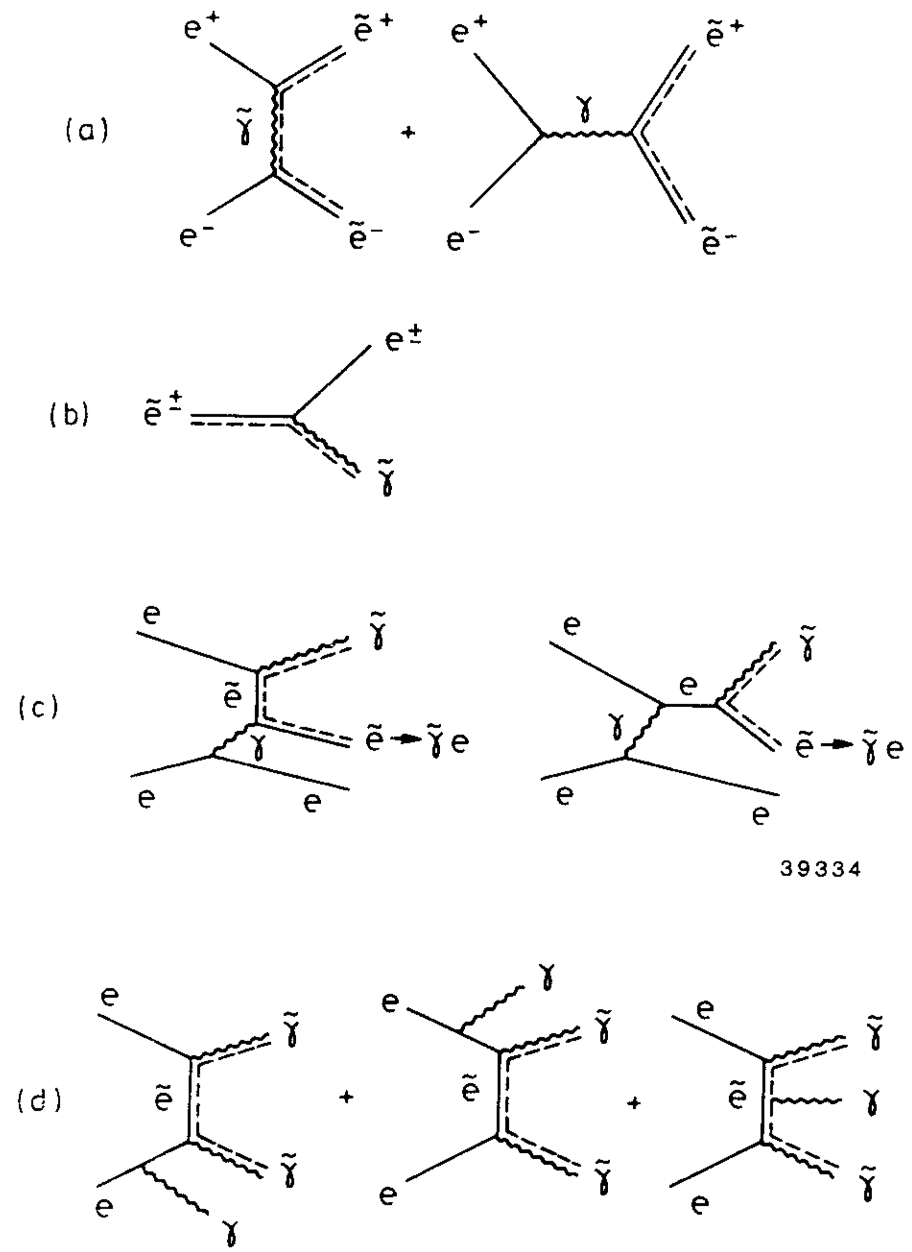

Fig. 3: Feynman diagrams for the production of the scalar electron (a and c) and stable photino (c and d) together with that for the decay of the scalar electron (b).

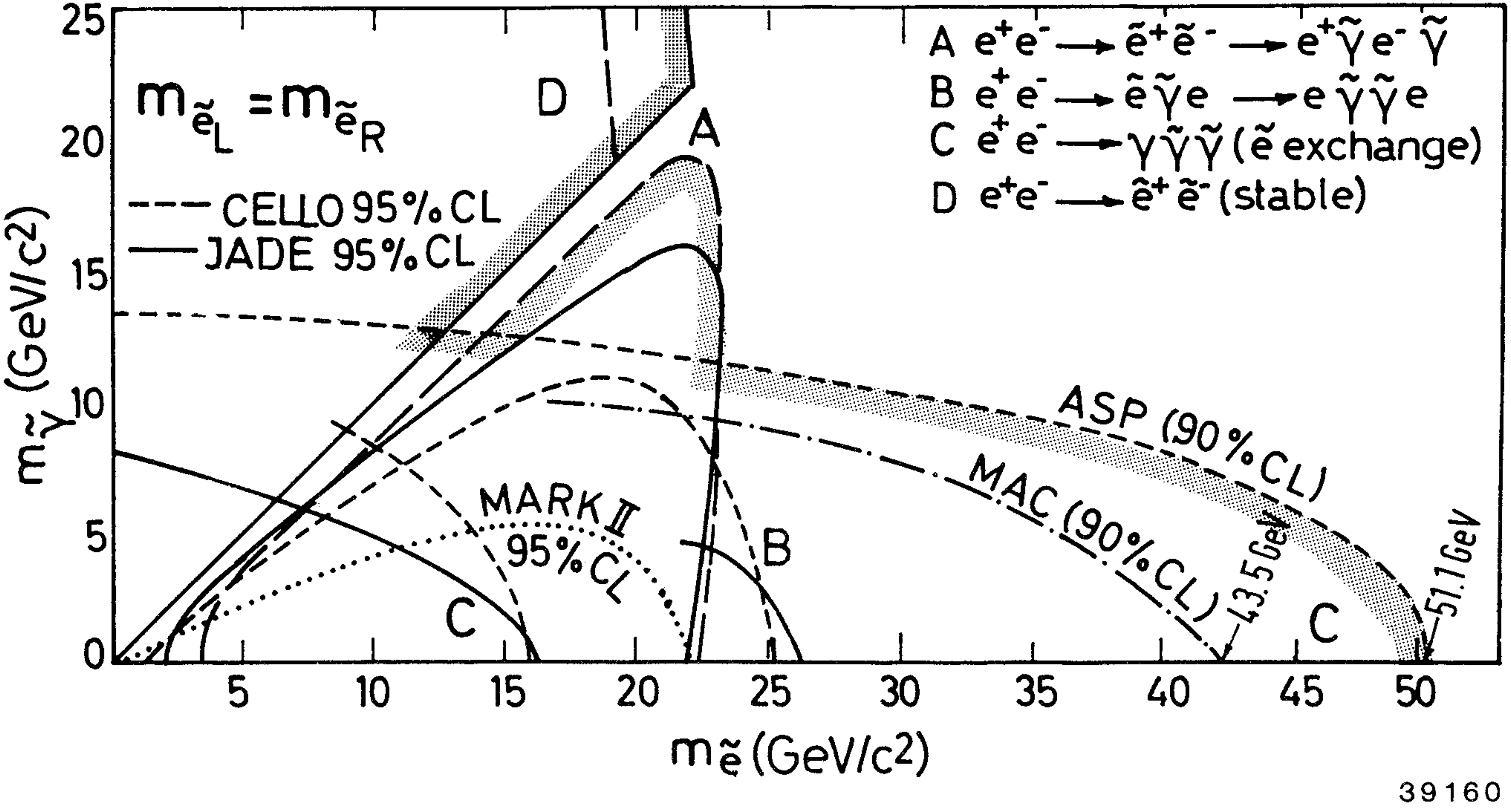

Fig. 4: Excluded region in the $M_{\tilde{\gamma}}$-$M_{\tilde{e}}$ plane for stable photino.

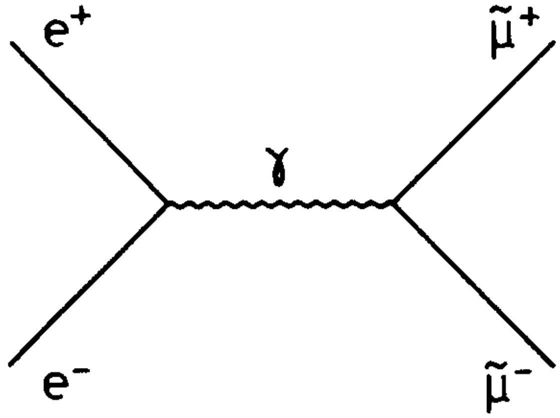

Fig. 5: Feynman diagram for the pair production of scalar muons $\tilde{\mu}$.

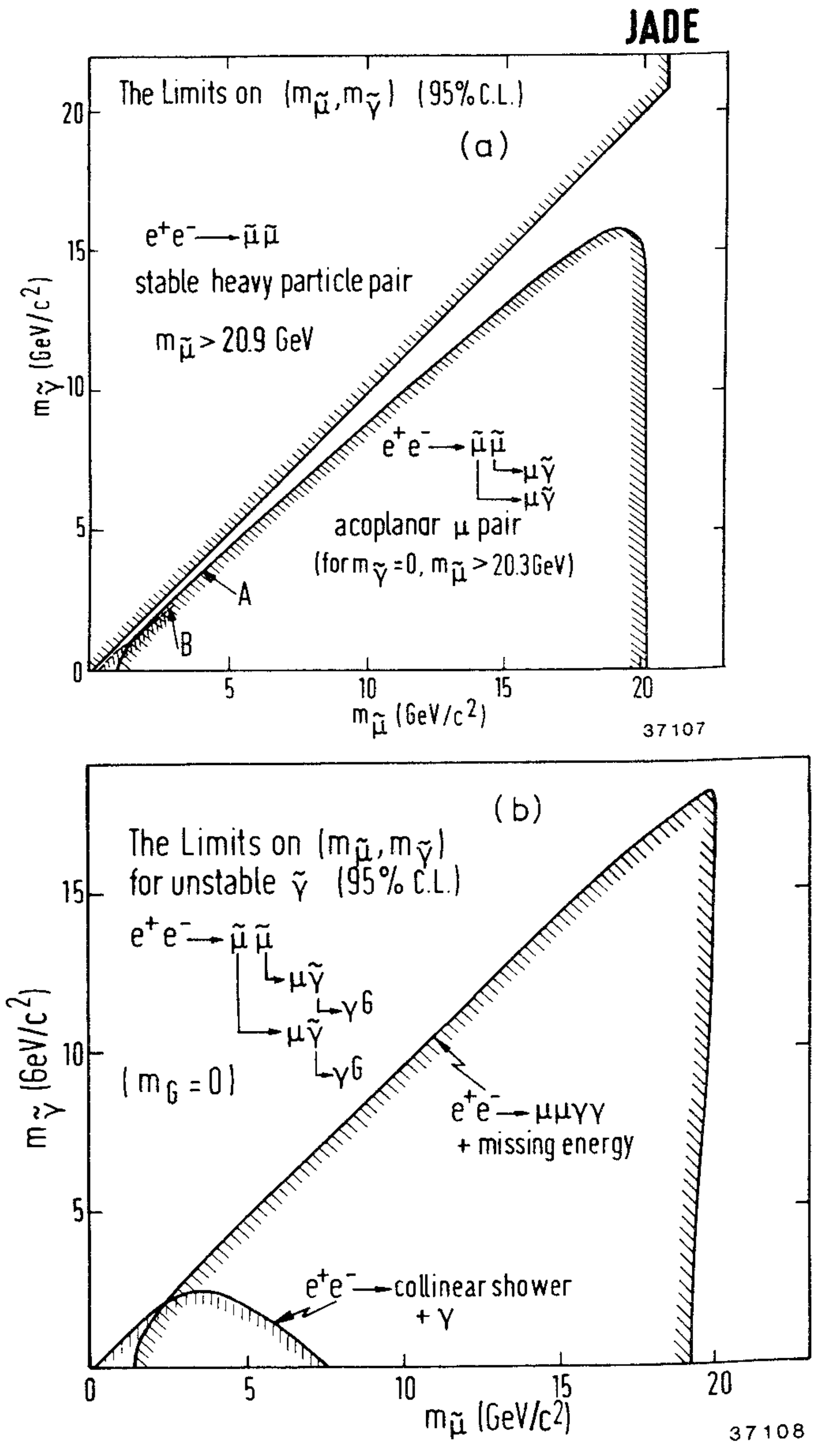

Fig. 6: Excluded region in the $M_{\tilde\gamma}$–$M_{\tilde\mu}$ plane for (a) stable and (b) unstable photinos. These results are from JADE.

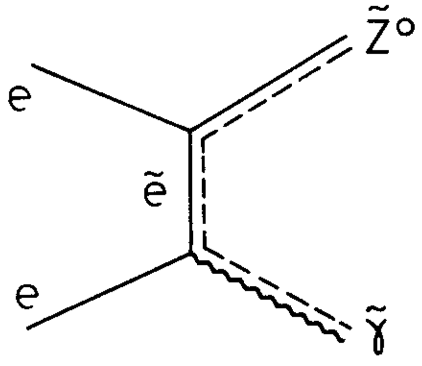

Fig. 7: Feynman diagram for the production of zino $\tilde{Z}^{O}$.

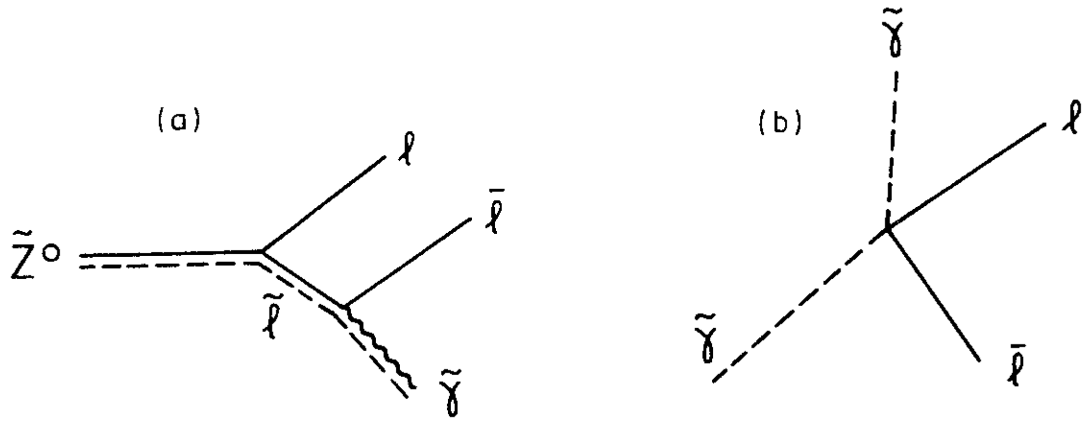

Fig. 8: Decay of $\tilde{Z}^{O}$ into $\ell\bar{\ell}\tilde{\gamma}$ and schematic diagram of the event.

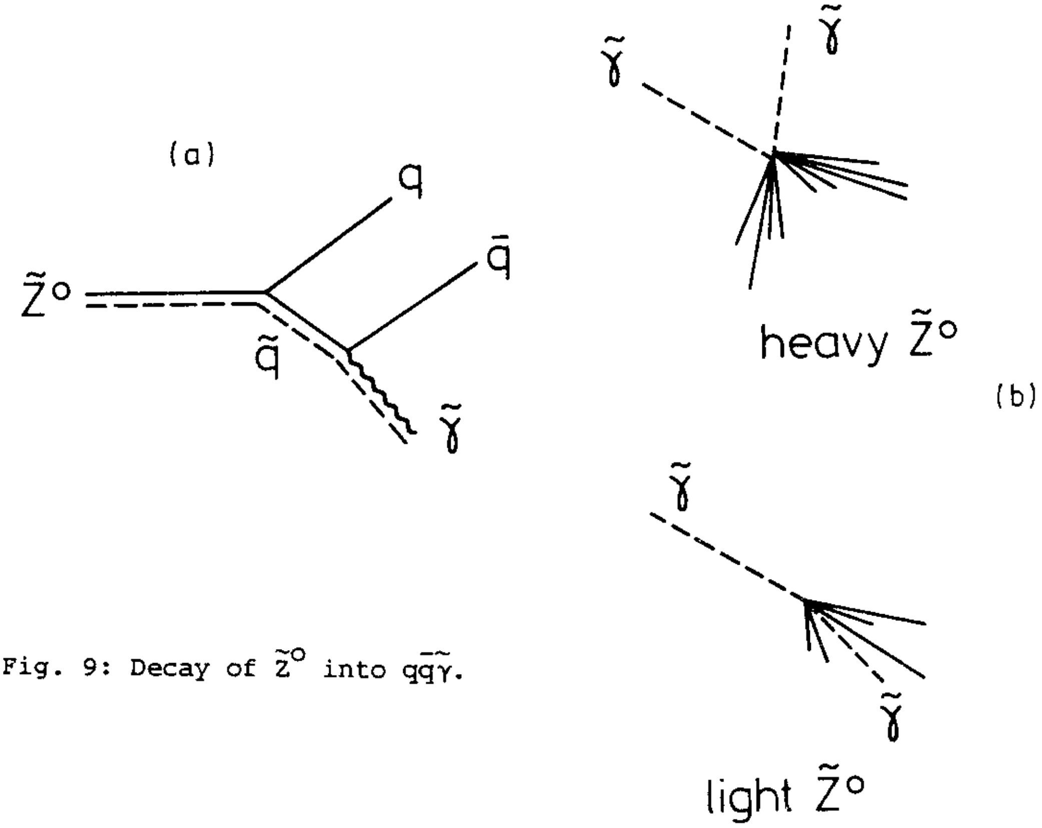

Fig. 9: Decay of $\tilde{Z}^o$ into $q\bar{q}\tilde{\gamma}$.

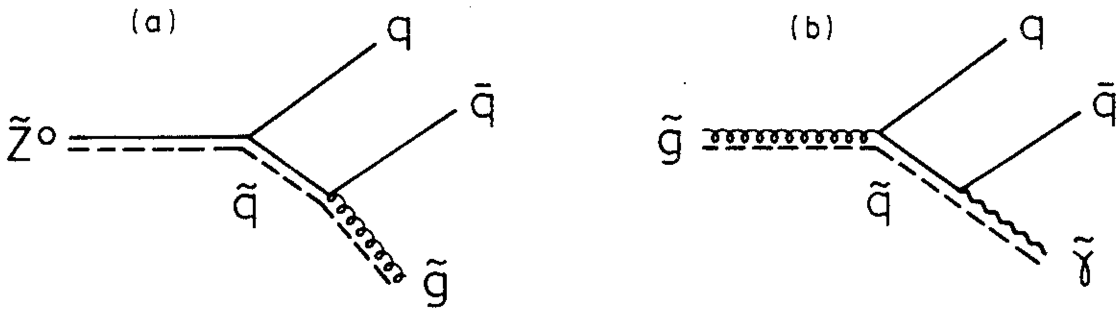

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Fig. 10: Decay of $\tilde{Z}^o$ into $q\bar{q}\tilde{g}$.

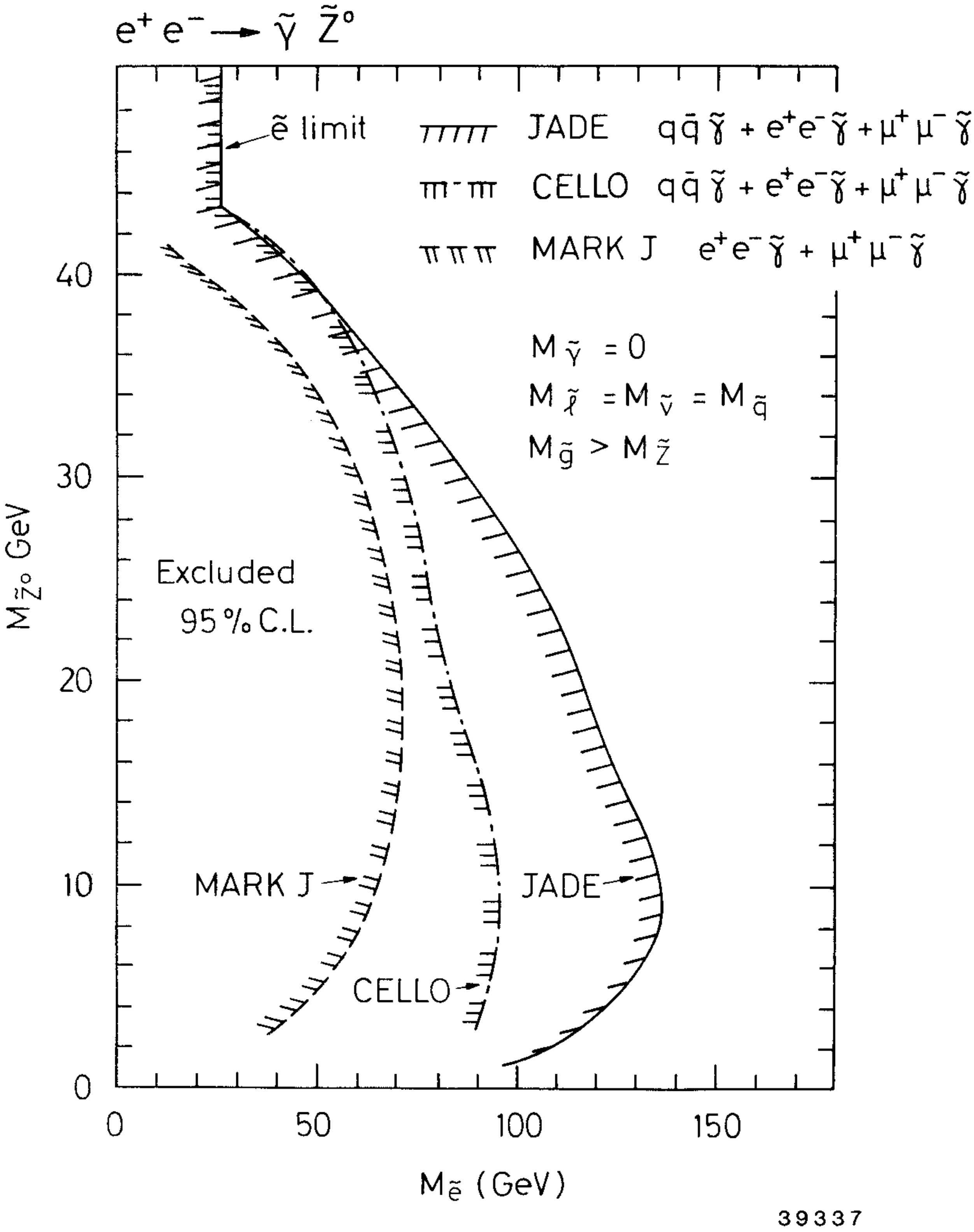

Fig. 11: Excluded region in the $M_{\tilde{Z}^o}$-$M_{\tilde{e}}$ plane from $\tilde{Z}^o \to \ell\tilde{\ell}\gamma$ and $q\tilde{q}\gamma$.

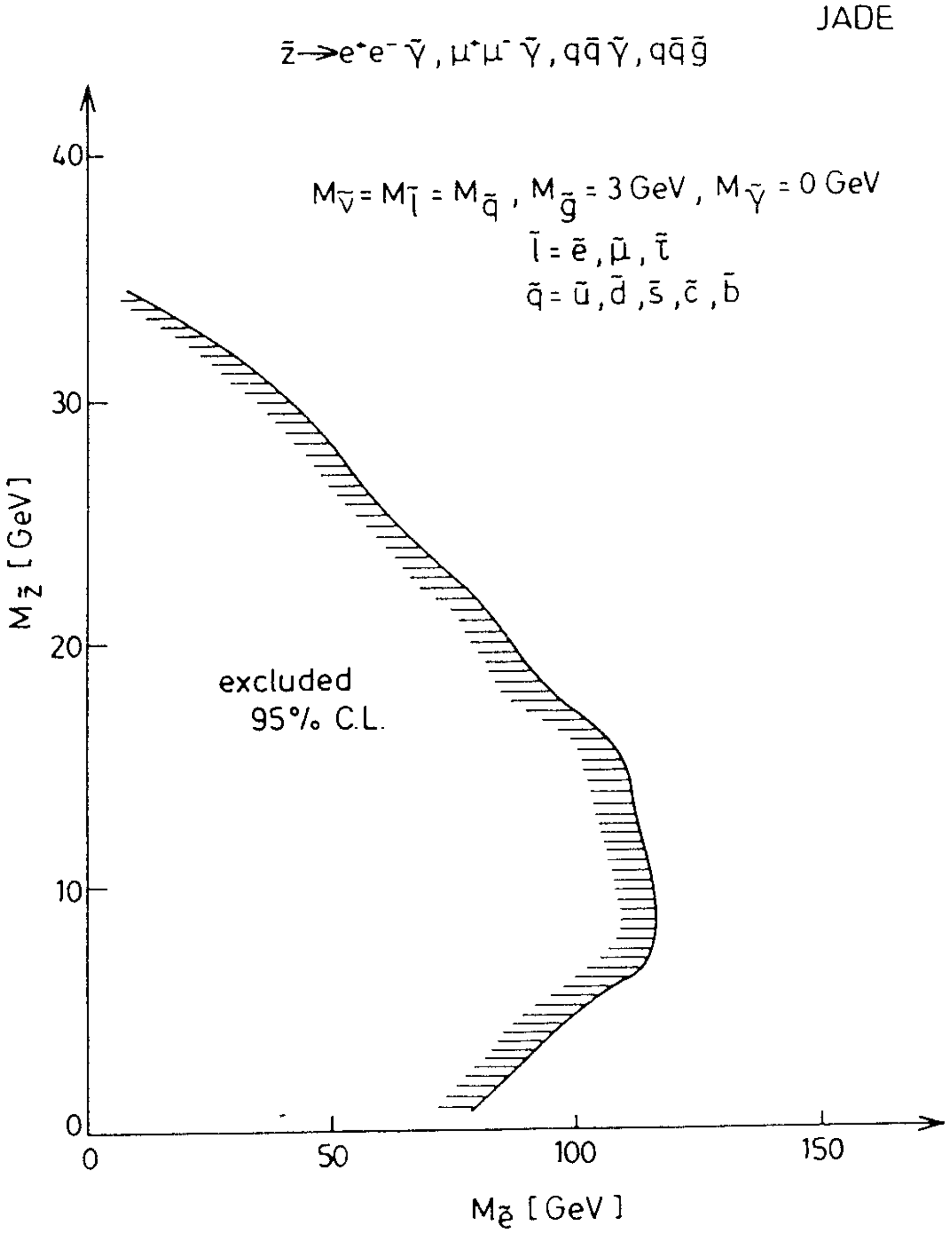

Fig. 12: Excluded region in the $M_{\tilde{Z}^0}$-$M_{\tilde{e}}$ plane under the assumption that $M_{\tilde{g}} = 3$ GeV.

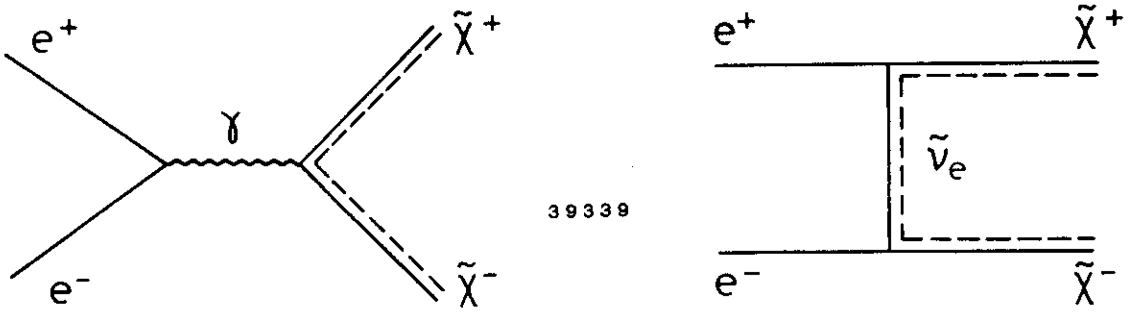

Fig. 13: Feynman diagrams for the production of charginos $\tilde{\chi}^{\pm}$.

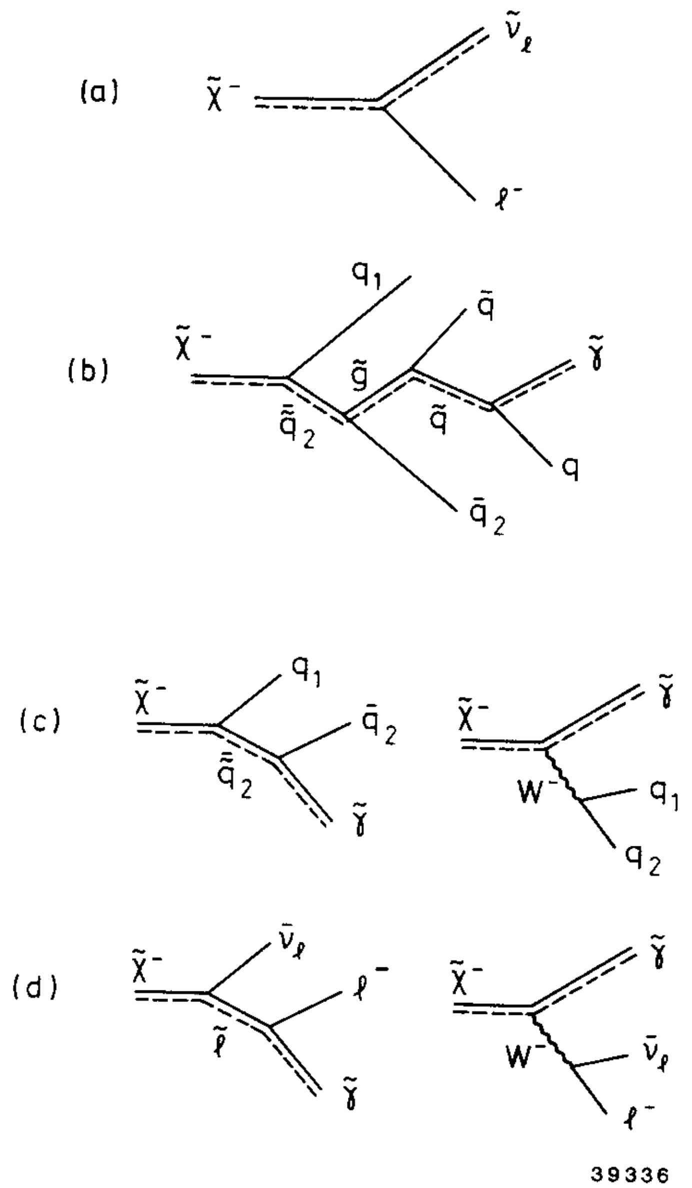

Fig. 14: Various decay modes of the charginos.

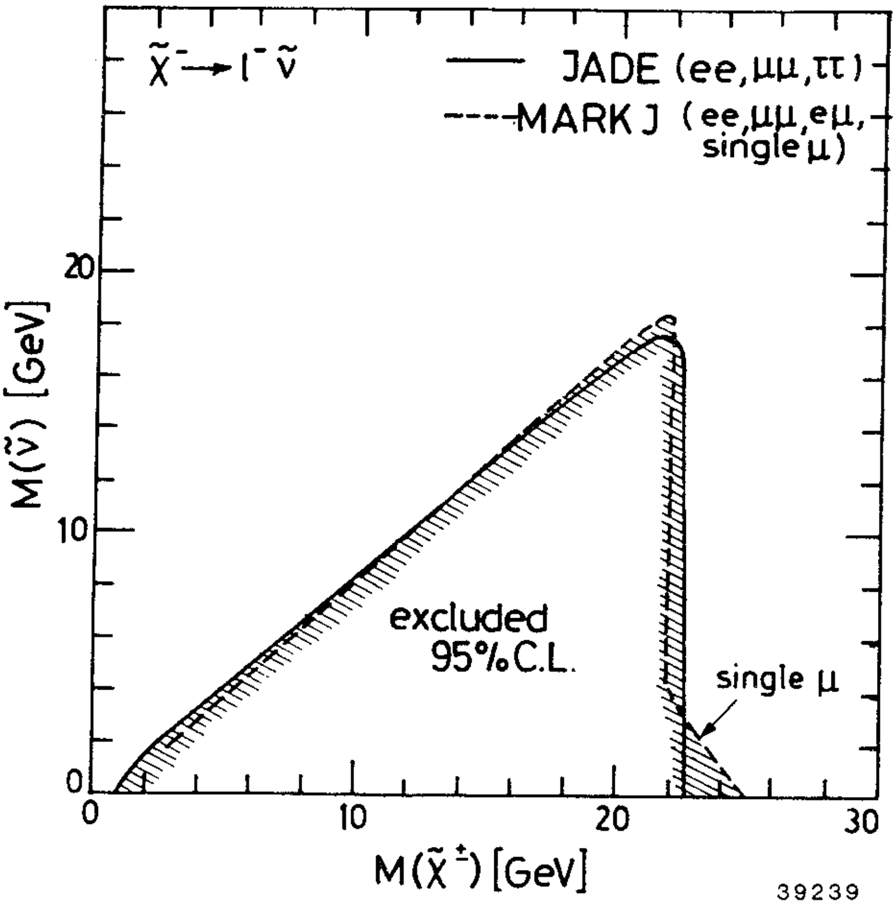

Fig. 15: Excluded region in the $M_{\tilde{\nu}}$-$M_{\tilde{\chi}}$ plane from the decay $\tilde{\chi}^{\pm} \to \ell^{\pm}\tilde{\nu}_{\ell}$.

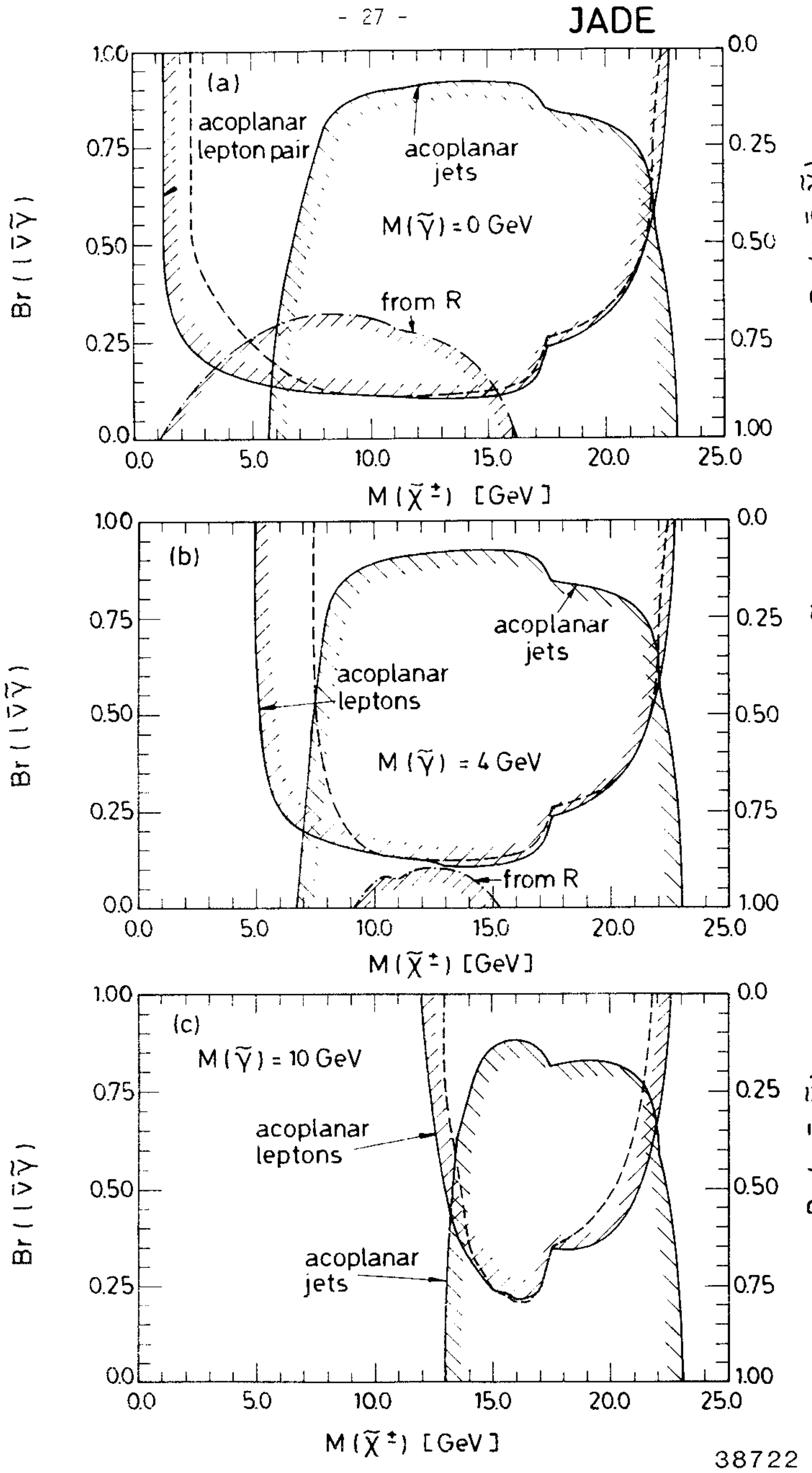

Fig. 16: The limits for chargino masses with 95% C.L. as a function of the leptonic branching fraction for chargino decay, for the case of $\tilde{\chi}^{\pm} \to \ell\nu\tilde{\gamma}$ or $\tilde{\chi}^{\pm} \to q_1\bar{q}_2\tilde{\gamma}$.