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Search for New Particles in e^+e^- Annihilation

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ABSTRACT

Recent results on search for new particles in e^+e^- annihilation are presented. Searches for new elementary fermions, Higgs particles, supersymmetric particles, and indications of compositeness all turn out to be negative and yield limits on particle masses. Some puzzling phenomena are discussed.

Suche nach neuen Teilchen in der e^+e^- Vernichtung

ZUSAMMENFASSUNG

Neuere Ergebnisse auf der Suche nach neuen Teilchen in der e^+e^- Vernichtung werden vorgestellt. Die Suchen nach neuen elementaren Fermionen, Higgs Teilchen, supersymmetrischen Teilchen und Hinweisen auf 'Compositeness' verliefen alle negativ und liefern Grenzen auf die Teilchenmassen. Einige ungeklärte Phänomene werden diskutiert.

Invited talk at the Tenth Hawaii Conference on High Energy Physics, Honolulu, 26. -31. August 1985

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1. INTRODUCTION

In this paper I will review the extended searches for new particles which have been performed at e^+e^- colliders[1]. Emphasis will be on results from the high energy machines where a wealth of data is now available from the experimental groups ASP, HRS, MAC, MARK II, and TPC at PEP and CELLO, JADE, MARK J, PLUTO, and TASSO at PETRA.

Many searches at the two machines are complementary in the sense that PETRA has concentrated on high energies accumulating some 20pb^{-1} per experiment between 40 and 47 GeV cm energy in the last two years (plus about 80 pb^{-1} at 35 GeV the year before). On the other hand PEP tuned the machine to high luminosities at 29 GeV where several experiments have integrated some 200 pb^{-1} in the last years.

Besides the high energy data I will also mention some new results which have been recently obtained by the CLEO and CUSB groups at CESR and the ARGUS detector at DORIS II around 10 GeV cm energy.

An excellent review of the field has been given recently by Komamiya at the Kyoto Conference[1].

To introduce searches for new particles let us first briefly look into the 'standard model' of elementary particle physics. It is based on the idea of local gauge symmetries which generate the strong, weak, and electromagnetic interactions with the gauge groups $SU_C(3) \times SU(2) \times U(1)$. The gauge bosons (gluons, Z^0, $W^\pm$, γ) mediate interactions between the structure particles of matter, the fermions. They come in two categories, quarks with and leptons without strong interaction. We believe today that at least three generations of quark and lepton doublets exist (Fig. 1a). Masses are given to Z^0, $W^\pm$ and the fermions by spontaneous symmetry breaking[2] (Higgs mechanism). Although most of the particles of the standard model described above have been discovered, there are still several open questions:

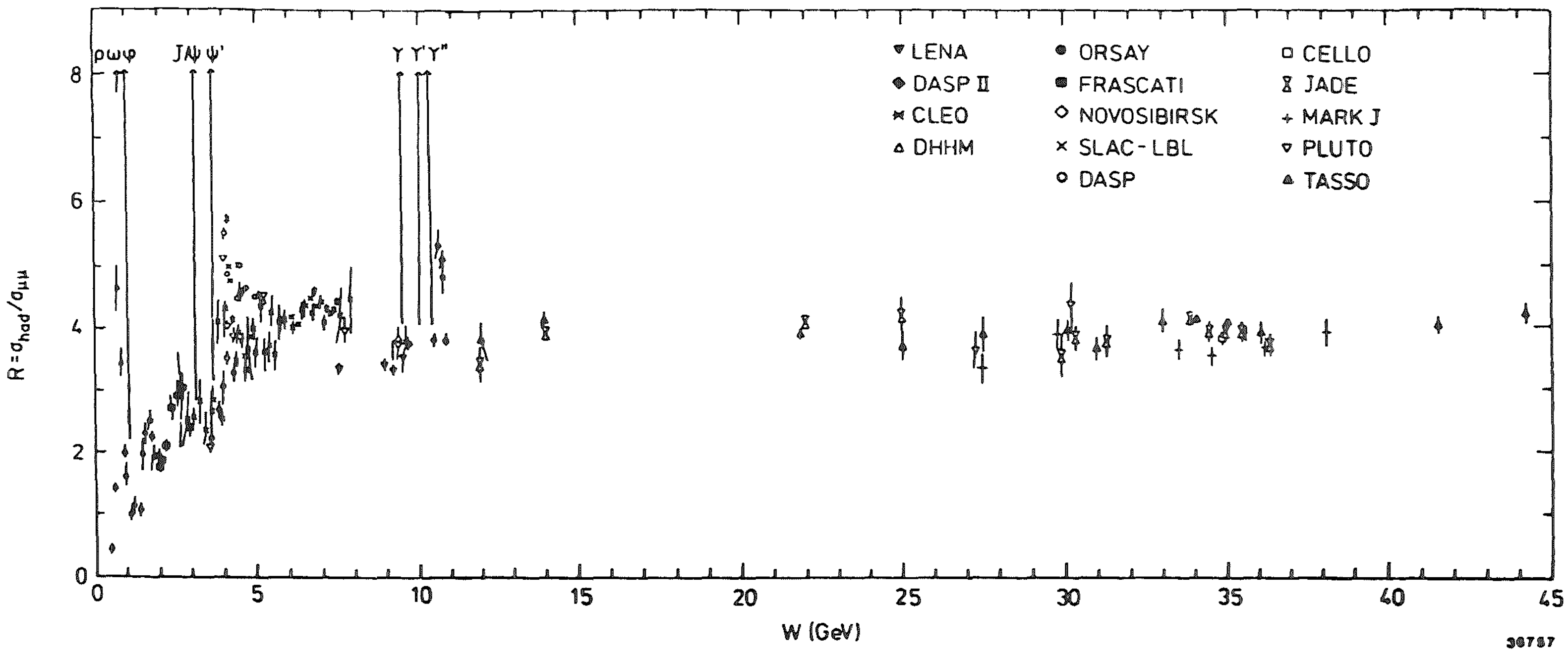


Fig. 1: Normalized total hadronic annihilation cross section $R = \sigma_{tot}/\sigma_{QED}$ as a function of the cm energy $W = \sqrt{s}$.

- there is only indirect (though overwhelming) evidence for the τ neutrino[3],
- the sixth quark (top) has not been discovered,
- we do not know how many generations of fermions there are,
- in the standard process of mass generation at least one new particle, the Higgs boson, is generated[2]. This particle has not been found yet.

In addition to these open questions within the standard model several problems and shortcomings of the model are encountered.

- A true unification of the three interactions as attempted in Grand Unified Theories GUT has been unsuccessful so far (see D. Perkins' talk[4]).
- Gravitation is not yet included in the standard model. The only promising path seems to lead through supersymmetry.[5,6]
- The way of generating masses is completely open. Attempts other than the Higgs mechanism have been tried, e.g. technicolour.[7]
- Why do fermions occur in several generations? This question - among others - leads to the suggestion of compositeness of quarks and leptons (and heavy gauge bosons)[8].

This review will deal with some aspects of those problems underlined above.

2. PARTICLE PRODUCTION IN e^+e^- REACTIONS

Charged particles are pairproduced in e^+e^- annihilation according to the simple formulae

$$\sigma_{1/2} = Q_q^2 \, \sigma_{QED} \, \beta \frac{(3-\beta^2)}{2} \quad \text{for spin } 1/2 \qquad (1)$$

$$\sigma_0 = Q_q^2 \, \sigma_{QED} \frac{1}{4} \beta^3 \quad \text{for spin } 0 \qquad (2)$$

Q_q = charge, $\beta = v/c$, $\sigma_{QED} = 4\pi\ \alpha^2/3s$
α = fine structure constant, s = (cm energy)^2.

Scalar particles are both suppressed by a spin factor 4 and a much slower increase of the threshold factor than spin 1/2 particles. At high energies the above cross sections are modified by electroweak effects. In particular, also neutral fermions can be produced according to

$$\sigma_N = \sigma_{QED}\,(a_e^2 + v_e^2)(a_f^2 + v_f^2)\left(\frac{G_F\ M_Z^2}{8\sqrt{2}\ \pi\alpha}\ \frac{s}{s - M_Z^2}\right)^2 \qquad (3)$$

with a, v being the axial and vector coupling constant for the electron and the outgoing fermion. G_F is the weak coupling constant and M_Z the mass of the Z^0. The expression in the last bracket is $\chi \simeq -0.06$ at $\sqrt{s}$ = 34 GeV and $\chi \simeq -0.10$ at $\sqrt{s}$ = 44 GeV.

A big advantage of particle searches in e^+e^- annihilation is the clean kinematical situation of producing particle pairs in the cm system (if we ignore higher order QED effects). For charged particles, the production according to (1) or (2) will asymptotically lead to an increase of the total cross section which is usually measured in terms of $R = \sigma_{tot}/\sigma_{QED}$: $\Delta R = Q_f^2$ for fermions and $\Delta R = 1/4\ Q_s^2$ for scalar bosons. So the first quantity to check is the total cross section.

Fig. 1 shows a compilation of e^+e^- total hadronic cross section data in terms of $R = \sigma(e^+e^- \to \text{hadrons})/\sigma_{QED}$ as a function of the cm energy $\sqrt{s}$.[9] The data are in good agreement with the expectation of

$$R = 3 \cdot \sum_q Q_q^2 \left(1 + \frac{\alpha_s}{\pi}\right) \qquad (4)$$

for 5 quark flavours including first order QCD corrections.

Disappointing as this may be from the point of view of particle searches, one may try and turn the vice into a virtue. First of all, the constancy of the cross section over a wide range of energy can be used to give a limit on the formfactor of the pairproduced quarks. Parametrizing the formfactor in the form $F(s) = 1 \pm s/(s - \Lambda_{\mp}^2)$ yields values of $\Lambda_{\pm} \simeq$ 200 ÷ 300 GeV which corresponds to an upper limit on the quark radius of $r_q \lesssim 10^{-18}$ m.[1]

Further results can be obtained if one compares the total cross section with the theoretical expectation

$$R = 3 \sum_q Q_q^2 (1 + \delta_{QCD})(1 + \delta_{e/w}) \tag{5}$$

including QCD corrections

$$1 + \delta_{QCD} = 1 + \alpha_s/\pi + C_2 (\alpha_s/\pi^2 \tag{6}$$

with $C_2 = 1.99 - 0.12\ N_f$ in the $\overline{MS}$ scheme and electroweak corrections

$$(1 + \delta_{e/w}) = 1 - 2 \frac{v_e v_q}{Q_q} \chi \tag{7}$$

$$v_f = \frac{Q_f}{|Q_f|} - 4\ Q_f \sin^2 \theta_w \quad .$$

Fig. 2 shows the world data on an expanded R-scale[10]. The experimental uncertainty on the data of 2 ÷ 3% is roughly of the same size as the expected corrections. This excludes precise determinations of α_s and $\sin^2\theta_w$. However, as shown in Fig. 2, data can be perfectly explained with both corrections in the right ballpark.

As far as new particle searches are concerned, this again shows that little room is left for new phenomena.

3. SEARCH FOR NEW ELEMENTARY FERMIONS

a) New Heavy Quarks

Although it is clear from Figs. 1 and 2 that no new threshold has been passed in e^+e^- annihilation, these measurements do not exclude yet

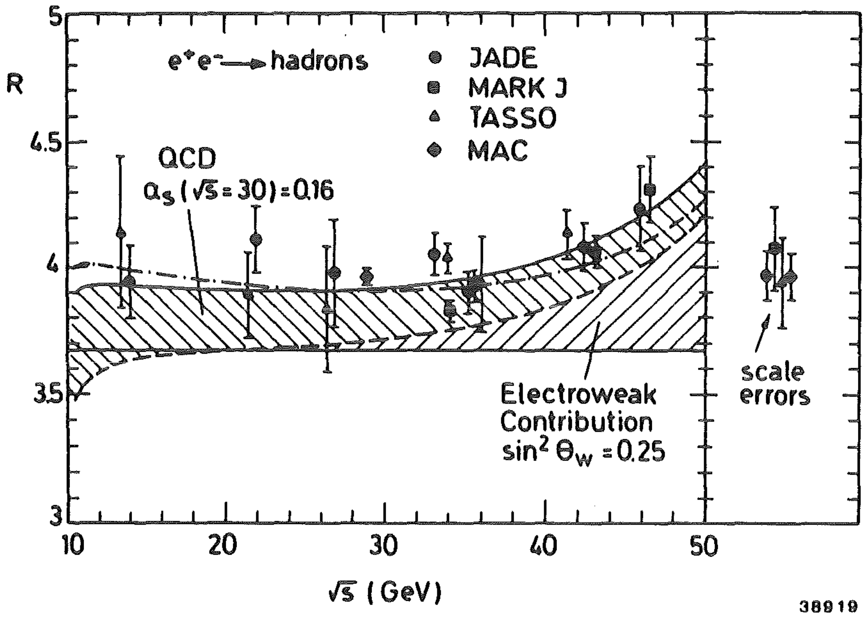


Fig. 2: Normalized total hadronic cross section R vs. energy on a zero suppressed scale. Data are compared with the quark parton model prediction including QCD and electroweak corrections.

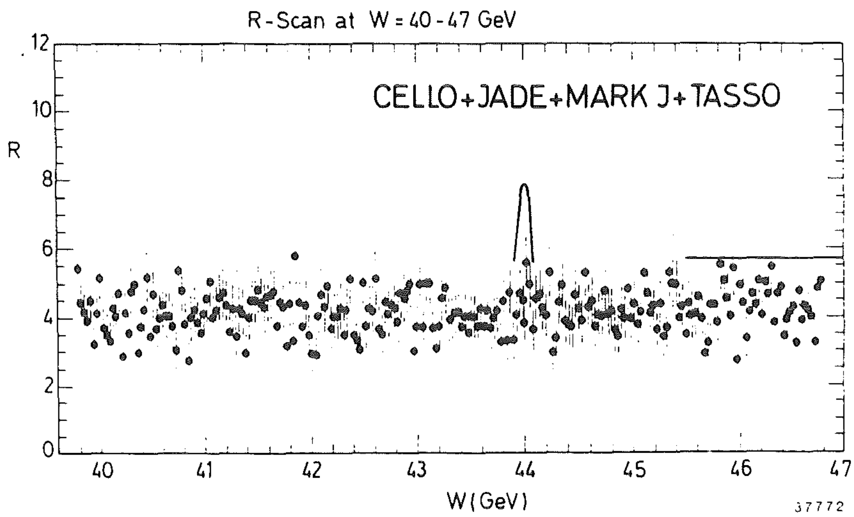


Fig. 3: Normalized total hadronic cross section vs. energy W = $\sqrt{s}$. R measured in steps of $\Delta(\sqrt{s})$ = 30 MeV. The expectation for a top quark and for toponium is indicated.

narrow resonances expected e.g. a few GeV below a new quark threshold.

During 1983 and 1984 a search for such narrow resonances has been performed at PETRA. The energy range between 39.8 GeV $\leq \sqrt{s} \leq$ 46.78 GeV was scanned in steps of $\Delta(\sqrt{s})$ = 30 MeV, well within the natural energy spread of the machine. On average 50 ÷ 60 nb^{-1} per point and experiment were accumulated.

The combined result of all four experiments (CELLO[11], JADE[12], MARK J[13], TASSO[14]) is shown in Fig. 3. A $t\bar{t}$ resonance, as indicated in the figure, can be safely ruled out. However, a bound state of $Q_q = -1/3$ quarks which would be 4 times smaller in R cannot be excluded from this measurement. A more sensitive measure for new quark production is the aplanarity, which is expected to increase strongly above threshold.

Fig. 4 shows the CELLO data compared to the expectation of an additional quark of charge 1/3 or 2/3. The 95% C.L. lower limits on the new quark masses are

$$M_t > 23.3 \text{ GeV} \qquad Q_t = 2/3$$

$$M_{b'} > 22.7 \text{ GeV} \qquad Q_{b'} = -1/3$$

A clean signature for new heavy quarks is the emission of leptons at large angle with respect to the event axis (thrust axis). Such events have been searched for by all PETRA collaborations. No indication for anything new was found except for an effect seen by the MARK J group[15] at highest PETRA energies (46.30 $\leq \sqrt{s} \leq$ 46.78 GeV). Fig. 5 shows their data at high energy compared to a control sample with about 10 times more events at lower energy. An excess of 6 events with low thrust (< 0.8) and large μ emission angle (cos θ < 0.7) with respect to the thrust axis was found. In a successive run with about the same integrated luminosity only 2 additional events were detected. Fig. 5 shows the full data sample with 8 events in the large angle, low thrust bin. From the control sample, a background of 0.5 events would have been expected. No excess events of

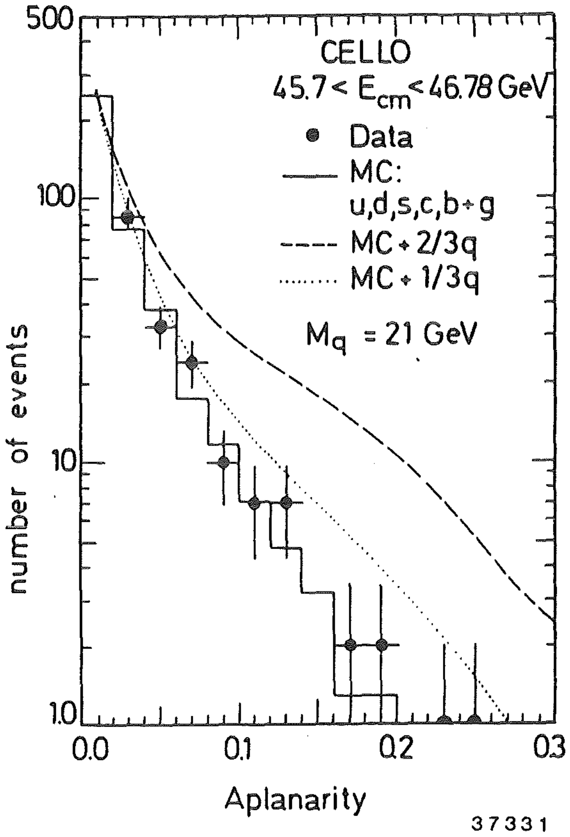


Fig. 4: Aplanarity distribution at highest PETRA energies compared with the expectation of an addition quark of charge 2/3 or -1/3.

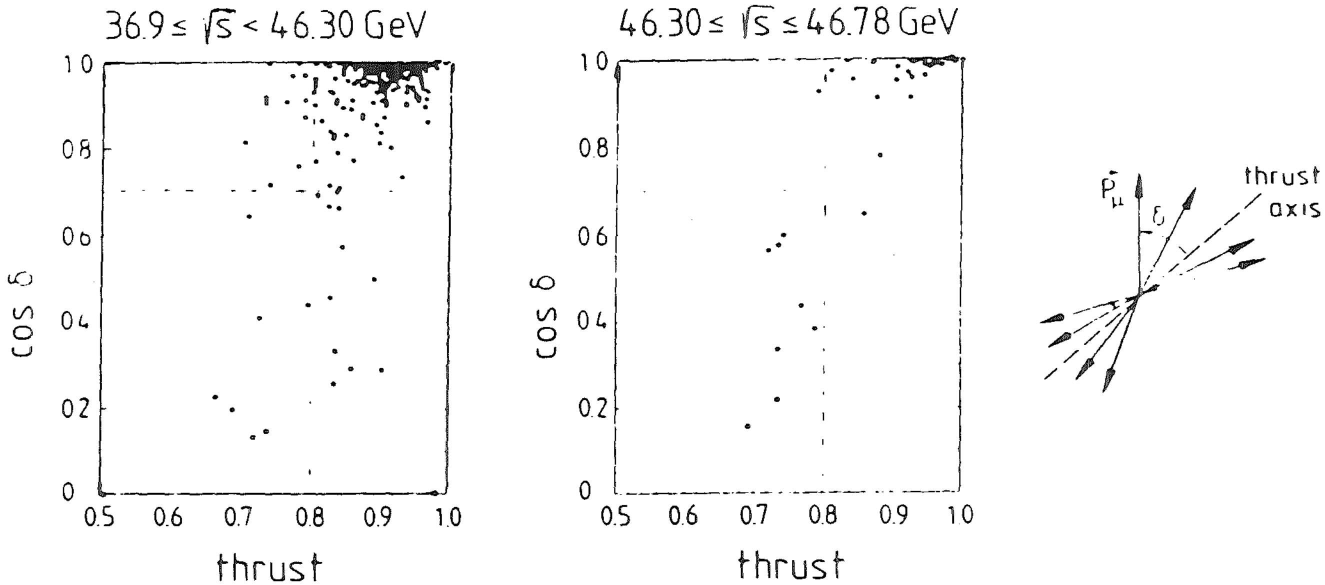


Fig. 5: Scatter plot of events as a function of thrust and cos δ. The low energy control sample contains about 10 times more luminosity.

this type above background have been seen by the other collaboration.

What are the prospects for toponium searches at the next e^+e^- colliders TRISTAN, SLC, and LEP? Fig. 6 shows the width for the 'background' continuum reaction $e^+e^- \rightarrow$ hadrons $R(\gamma, Z)$ compared to the heavy vector meson ($t\bar{t}$) width at LEP[16]. One can see that with increasing energy the signal : noise ratio will decrease from about 3:1 at 60 GeV to 1:2 at 80 GeV. If the toponium mass is even closer to the Z^0 mass, interference effects will cause dramatic variations of the cross section (Fig. 7).

3b. Further Sequential Leptons

If further generations of lepton doublets (L^-, ν_L) would excist in the accessible mass range, they would be rather easily detectable through their decay into the known quarks and leptons. In case they would have the conventional coupling to the charged weak current, their decay rates into the different decay channels can be readily predicted (see Fig. 8a). Assuming equal coupling to all (colour factor 3 for the quarks) fermion doublets we can estimate a leptonic branching ratio of about 12% for each of the decays into e, μ, τ. The signatures for the searches all make use of the acoplanarity of the events due to the missing energy of the neutrinos. MARK II has looked for anomalous lepton pairs, JADE searched for acoplanar hadron jets and CELLO, MAC, MARK J, PLUTO, and TASSO studied the cleanest signature of leptons against hadrons with missing energy. Recent new results at the 95% C.L. are $M_L > 22.0$ GeV (CELLO), $M_L > 22.5$ GeV (MARK J), and $M_L > 22.7$ GeV (JADE).

If ν_L is heavy it may mix with the light neutrinos. Heavy neutrinos ν_L can be pairproduced via a virtual Z^0 and decay according to the diagram of Fig. 8b. The coupling to the charged current is given by the mixing angle $\sin \varepsilon$. If the mixing is small or ν_L is light the particle may have a lifetime long enough to decay in the detector. The MARK II group has searched for secondary vertices between 2 mm and 100 mm from the interaction point in events containing $\geqslant 4$ tracks. They found 3 events with an estimated background of 2 events. Their result is shown in Fig. 9a for

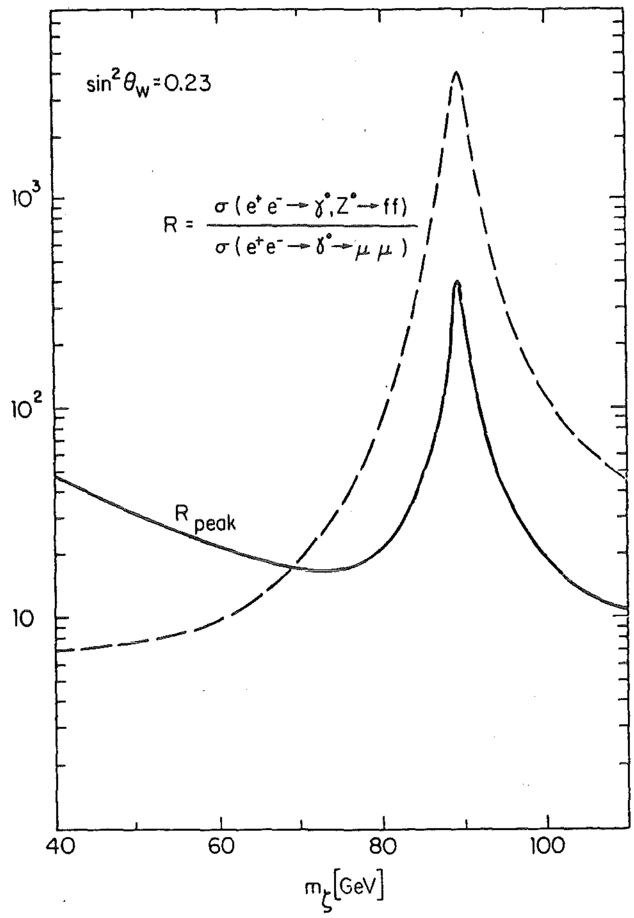


Fig. 6:
Expected normalized cross section R for the heavy vector meson production R^{peak} compared to the continuum of hadronic annihilation (dashed line) as a function of energy ($m_{\xi} = \sqrt{s}$).

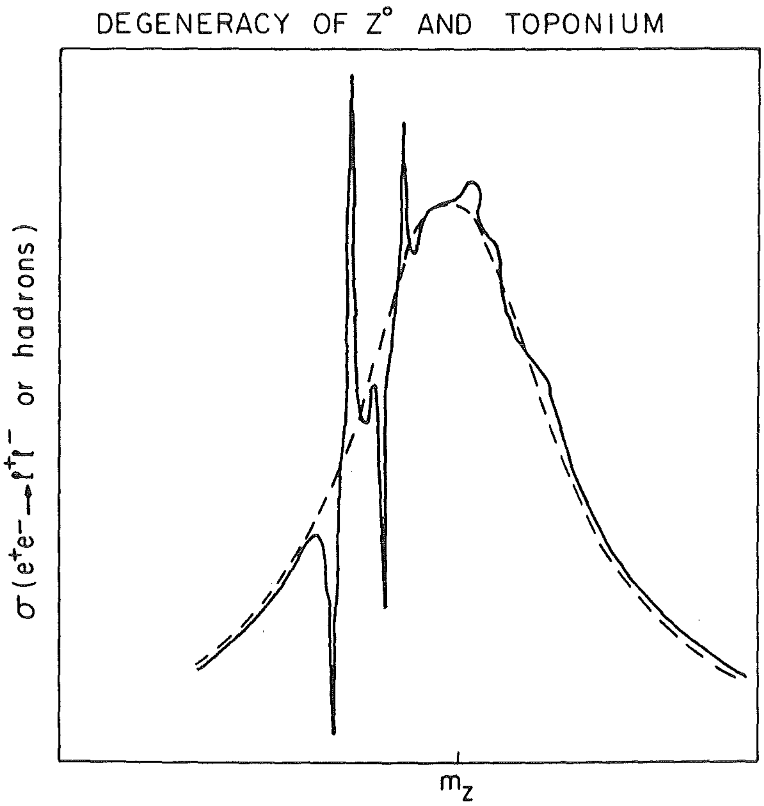


Fig. 7:
Destructive interference expected for toponium masses close to the Z^0 mass. The variation of the total hadronic cross section with energy near the Z^0 mass is shown.

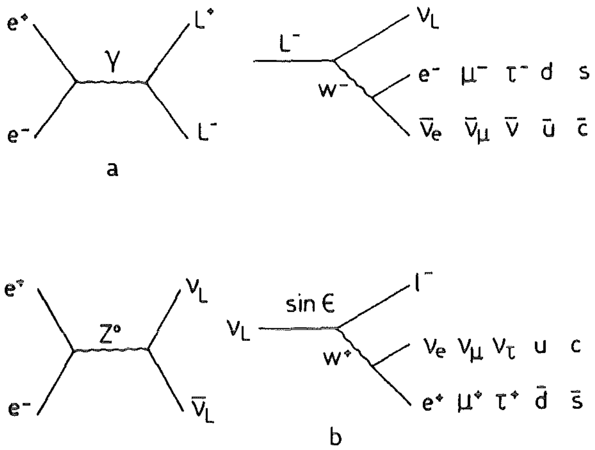


Fig. 8a:
Decay of a hypothetical sequential lepton L into the known fermions and the signatures used for the search.
8b:
Weak decay of a hypothetical heavy neutrino ν_L.

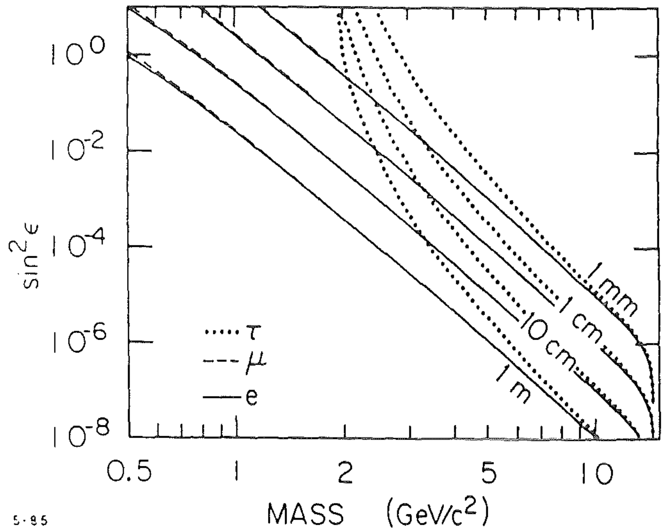


Fig. 9a
Excluded mass range for heavy neutrinos as a function of the mixing angle $\sin^2 \varepsilon$.

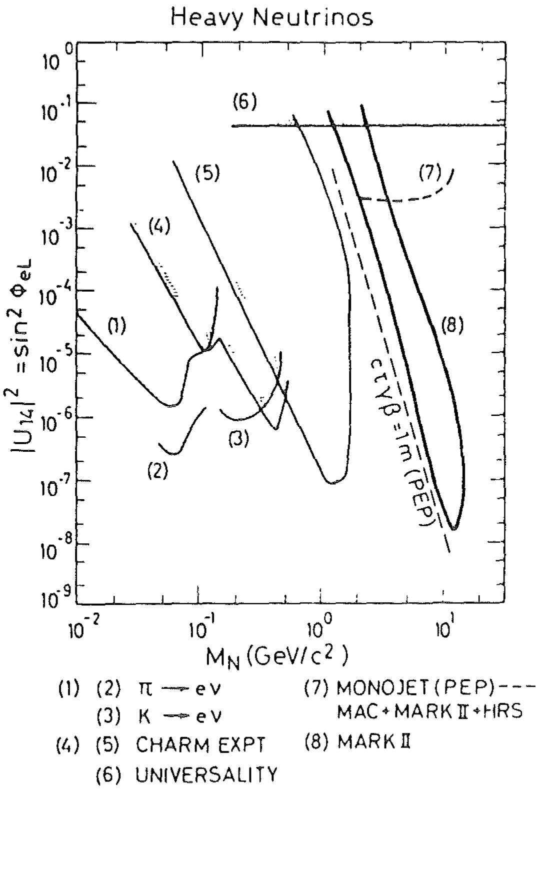


Fig. 9b
As a), summarizing limits from $\pi \to e\nu$ (1), (2), $K \to e\nu$ (3), CHARM experiment (4), (5), universality (6), PEP monojet search (7), and MARK II (8).

the three cases of e, μ, τ mixing. For comparison limits from other experiments and the monojet search at PEP are included in Figure 9b.

Shortlived heavy neutrinos decaying into e (HRS) or ν (MARK II) plus two charged particles have been studied at PEP. The search excludes heavy neutrino masses between 2 and 5.4 GeV (90% C.L.) if a standard production cross section is assumed.

4. SEARCH FOR HIGGS PARTICLES

In the standard model one (complex) Higgs doublet is needed to generate the $W^{\pm}$ and Z^0 masses. In this minimal model one new physical particle, the neutral Higgs boson H^0, is generated. In other models, in particular in supersymmetric models, more Higgs particles are required and charged Higgs particles $H^{\pm}$ are expected[6]. Furthermore, technicolour models in which the heavy vector bosons are composite generate further scalar bosons, the technipions, which are predicted to have masses in the range of 5 to 14 GeV.[7]

4a. Neutral Higgs Particles

I will first discuss the standard model Higgs particle H^0 and then proceed to charged Higgs particles and technipions. Non-minimal neutral Higgs particles will be discussed in section 5 in the context of monojets.

$$Q\bar{Q}\ ({}^3S_1) \rightarrow H^0 + \gamma \tag{8}$$

The relative decay width is given by

$$\frac{\Gamma(Q\bar{Q} \rightarrow H^0\gamma)}{\Gamma(Q\bar{Q} \rightarrow e^+e^-)} \simeq \frac{G_F\, M^2_{Q\bar{Q}}}{4\sqrt{2}\ \pi\alpha} \left(1 - \frac{M^2_{H^0}}{M^2_{Q\bar{Q}}}\right) \tag{9}$$

Experimentally this reaction would reveal itself in a monochromatic γ line. Searches have been carried out on the J/Ψ and Υ resonance[18].

On the J/Ψ resonance BR $(J/\Psi \to H^0\gamma) \simeq 1/2 \cdot 10^{-4}$ is expected. The experimental limit of the Crystal Ball group[19]

$$BR(J/J\Psi \to \gamma + \text{nothing}) < 1.4 \cdot 10^{-5} \text{ (90\% C.L.)}$$

is sufficient to exclude H^0 if it does not decay in their detector. From the known mass-lifetime relation for H^0 they can deduce

$$M_{H^0} > 50 \text{ MeV}.$$

The exclusive $\xi(2.2)$ claimed by the MARK III collaboration is not considered to be a candidate for the standard Higgs particle[18] because its branching ratio

$$BR(J/\Psi \to \xi\gamma) \cdot BR(\xi \to K^+K^-) \simeq (5.8 \pm 1.8 \pm 1.5) \cdot 10^{-5}$$

would require unrealistic values for BR$(\xi \to K^+K^-)$ to be compatible with (9).

On the Υ resonance, BR$(\Upsilon \to H^0\gamma) \simeq 2 \cdot 10^{-4}$ is expected. Recently new experimental limits became available

ARGUS:	$< 0.2\ \%$	$E_\gamma = 0.5 \div 4.0$ GeV	[21]
CLEO :	$< (0.1 \div 1.4)\%$	$E_\gamma = 0.1 \div 2.0$ GeV	[22]
CUSB :	$< 0.02\ \%$	$M_{H^0} = 1.2 \div 4.2$ GeV	[23]

The latter one seems to exclude Higgs bosons in the mass range 1.2 GeV < M_{H^0} < 4.2 GeV, however radiative corrections to the simple process (8) may be rather large (about factor 2). Therefore we have to wait for a better (at least twice) experimental limit before we can draw any final conclusions.

The best place to look for H^0 would of course be the decay of $t\bar{t}$ $(^3S_1) \to H^0\gamma$. For $M_{t\bar{t}} \simeq 80$ GeV and $M_{H^0} \simeq 40$ GeV the branching ratio would be $\simeq 3\%$.

Another way to produce H^0 is through the decay of the Z^0 boson as shown in Fig. 10. The expected rates for 10^6 Z^0 decays which corresponds to about 1 year of running at LEP are given in Table 1 [24].

TABLE 1: Rates for 10^6 Z^0 decays

M_{H^0} (GeV)	10	20	30	40	50
$Z^0 \to H^0 \ell^+ \ell^-$	65	26	11	4	1.5
$Z^0 \to H^0 \gamma$	1.8	1.7	1.4	1.1	0.7

We see that in particular for high H^0 masses reaction (8) seems to be by far more promising to look for H^0.

4b. Charged Higgs Particles and Technipions

Charged Higgs particles would be produced according to formula (2) in e^+e^- reactions. As mentioned above, the reaction is strongly suppressed near threshold. Therefore mass limits will be lower than in the case of charged fermions. The Higgs will decay preferentially into the heavy fermions:

$$H^- \to \bar{c}b,\ \bar{c}s,\ \nu_\tau\ \tau^- \qquad (10)$$

Since the relative decay width into leptonic and hadronic channels cannot safely be predicted, experiments have to look for all decay modes. The leptonic decay has a rather simple signature, very similar to the one of a new heavy lepton. However, the decay into a quark pair is more difficult to detect since it involves four-jet final states. This decay mode was studied by TASSO[25]. The result is shown in Fig. 11 together with limits obtained by other experiments[26,27,28,29,30]. The range 5 GeV $< M_{H^\pm} <$ 13 GeV is excluded independent of the branching ratios. This shows in particular that charged technipions do not exist!

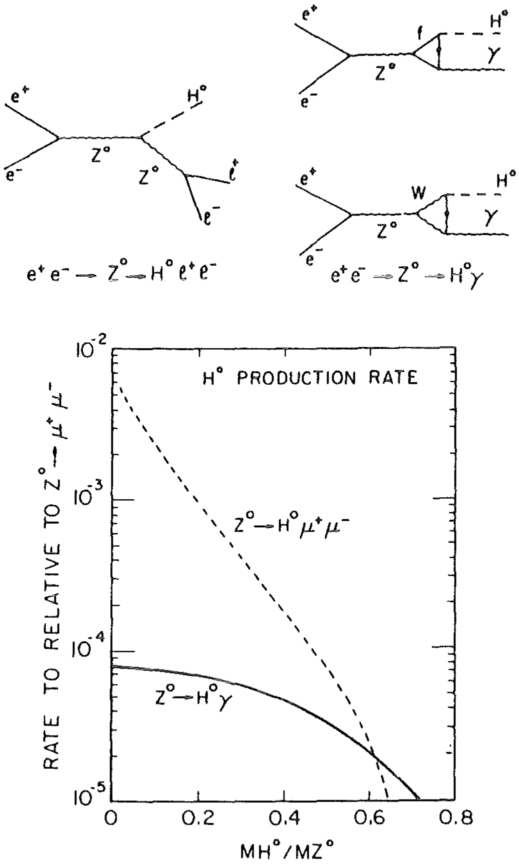


Fig. 10: H^0 production on the Z^0 resonance. Relative rate as a function of the H^0 mass.

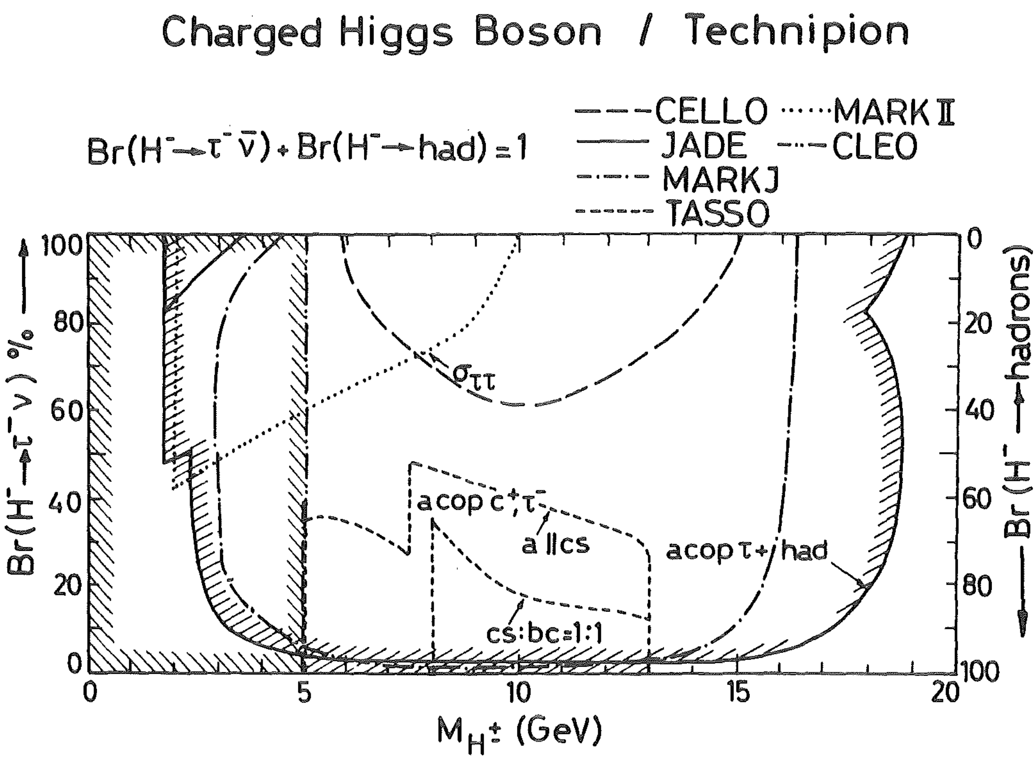


Fig. 11 Excluded mass ranges for technipions and charged Higgs particles as a function of the leptonic branching ratio.

5. SEARCH FOR SUPERSYMMETRIC PARTICLES AND MONOJETS

Supersymmetry (SUSY)[5] relates fermions and bosons by the symmetry operation J ±1/2. Thus, each standard particle has its SUSY partner with spin J ±1/2. Table 2 summarizes the minimal SUSY extension of the standard model[6]. Note that two Higgs doublets are necessary to preserve the one to one correspondence between Higgs and Shiggs. The SUSY partners of the vector boson and Higgs sector can mix to form neutralinos and charginos. In the following I will concentrate on new results on sleptons, photinos, neutralinos, and gluinos and refer to previous papers for earlier results[1].

TABLE 2: Supersymmetric Particles

Standard particles		J ± 1/2	Supersymmetric sparticles	
	J = 1/2			J = 0
Quark	q_L q_R q=u,d...		Squark	$\tilde{q}_L$ $\tilde{q}_R$ q=u,d...
Lepton	ℓ_L ℓ_R ℓ=eμτ		Slepton	$\tilde{\ell}_L$ $\tilde{\ell}_R$ ℓ=eμτ
Neutrino	ν_e ν_μ ν_τ		Sneutrino	$\tilde{\nu}_e$ $\tilde{\nu}_\mu$ $\tilde{\nu}_\tau$
	J = 1			J = 1/2
Gluon	g		Gluino	$\tilde{g}$
W-Boson	$W^\pm$		Wino	$\tilde{W}^\pm$ (Charge-inos)
Z-Boson Photon	Z^0, γ		Zino Photino	$\tilde{Z}^0$ $\tilde{\gamma}$ (Neutra-linos)
	J = 0			
Higgs	H_1^+ H_2^0 H_1^0 H_2^-		Shiggs	$\tilde{H}_1^0$ $\tilde{H}_2^0$ (Neutra-linos); $\tilde{H}_1^+$ $\tilde{H}_2^-$ (Charge-inos)

SUSY particles have the same couplings and quantum numbers as their conventional partners. However, mass differences between the partners will be generated by SUSY breaking. In many models this is assumed to occur at the Fermi scale. SUSY particles have a new conserved multiplicative quantum number R which is -1 for SUSY particles and +1 for conventional particles. Therefore, SUSY particles are always pair produced.

A particular consequence of this last property is that the lightest SUSY particle (LSP) will be stable since it cannot decay into light conventional particles without violating R-parity. Also, since all interactions with matter will involve SUSY particles which are known to be heavy of the order of $\gtrsim$ 20 GeV, the LSP will be almost non-interacting at present energies, i.e. will be neutrino like. The best candidates are the photino $\tilde{\gamma}$, Goldstino $\tilde{G}$, scalar neutrino $\tilde{\nu}$ and the higgsino $\tilde{h}_o$. (The Goldstino is the Goldstone particle generated in SUSY breaking. It does not exist in supergravity, since it will give mass to the gluino.)

All SUSY particles eventually decay into the LSP. Thus, the most important signature for SUSY will be the missing energy and momentum carried away by the LSP.

5a. Photinos and Scalar Electrons

Many SUSY models assume the photino $\tilde{\gamma}$ to be the LSP. To search for it one may try to study the SUSY analogue of the reaction $e^+e^- \rightarrow \gamma\gamma$ shown in Fig. 12d

$$e^+e^- \rightarrow \tilde{\gamma}\,\tilde{\gamma}\,. \tag{11}$$

As $\tilde{\gamma}$ is supposed to interact only very weakly it will be invisible in the detector. Therefore, the only way to study this process experimentally would be through initial state radiation (Fig. 12c) as suggested by Fayet[31]

$$e^+e^- \rightarrow \tilde{\gamma}\,\tilde{\gamma}\,\gamma\,. \tag{12}$$

The expected cross sections at $\sqrt{s}$ = 40 GeV for $x_\gamma > 0.2$ and $|\cos\theta_\gamma| <$ 0.87 are

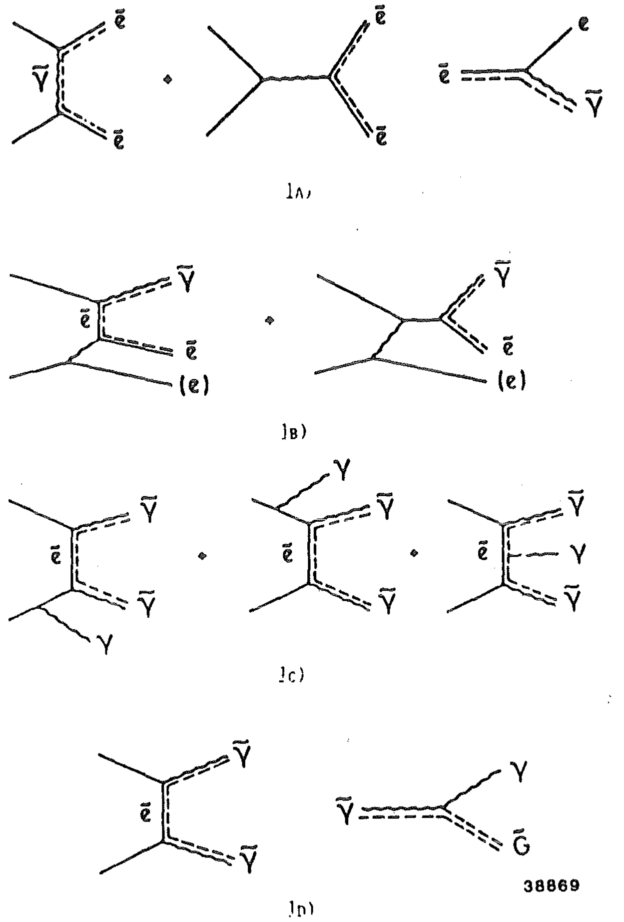


Fig. 12 Processes relevant for the search for scalar electrons and photinos

a) $e^+e^- \to \tilde{e}\tilde{e} \to e^+e^- + \tilde{\gamma}\tilde{\gamma}$

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

beampipe

c) $e^+e^- \to \tilde{\gamma}\tilde{\gamma}\gamma$

d) $e^+e^- \to \tilde{\gamma}\tilde{\gamma}$

$$\sigma(\tilde{\gamma}\ \tilde{\gamma}) \sim 0.3 \text{ pb} \quad \text{for} \quad M_{\tilde{e}} = 20 \text{ GeV}$$
$$\sim 0.1 \text{ pb} \quad \text{for} \quad M_{\tilde{e}} = 40 \text{ GeV}$$

which would lead to a signal of 10 ÷ 30 events for 100 pb^{-1}. The experimental problems of triggering on a single photon of $E_\gamma \simeq 2 \div 3$ GeV and nothing else with such a low event rate are formidable. One has to cope with a high background of higher order QED processes ($ee\gamma$, $\gamma\gamma\gamma$) and cosmic rays. Therefore, the experiment needs a good directional photon detection and nearly complete coverage for the missing energy.

Even in a perfect detector, the background of reactions of the type $e^+e^- \rightarrow \gamma\nu\bar{\nu}$ will remain. Fig. 13 shows the energy dependence of the SUSY process compared to this 'neutrino counting' reaction[32]. As one can see, experiments will be swamped by $\nu\nu\gamma$ reactions above $\sqrt{s} \simeq 50$ GeV. Thus PEP and PETRA are the only e^+e^- machines appropriate for the $\tilde{\gamma}\tilde{\gamma}\gamma$ reaction.

In view of this singular situation, the CELLO detector has been upgraded for full angular coverage for electromagnetic showers down to 50 mrad. Energy, time and direction of single photons is detected in the finely segmented LAr calorimeter at $|\cos\theta_\gamma| \leqslant 0.87$. At PEP, the ASP experiment[33] has been particularly designed for reaction (11). It consists of a central proportional chamber (PC) system surrounded by lead glass blocks sandwiched in 6 layers of PC's in the centre and additional forward calorimeters. The detector can be triggered by single photons down to 20^0 and has a hermetic coverage for electromagnetic showers down to 20 mrad.

As one can see from Fig. 12c,d the search for $\tilde{\gamma}$ is always intimitely connected with a search for scalar electrons. In Fig. 12 two other reactions relevant for the $\tilde{e}$ and $\tilde{\gamma}$ search are added: the $\tilde{e}\tilde{e}$ pair production (Fig. 12a) and the virtual compton scattering process of Fig. 12b where one electron remains undetected in the beam pipe.

The processes of Fig. 12 have been investigated by many groups. Fig.

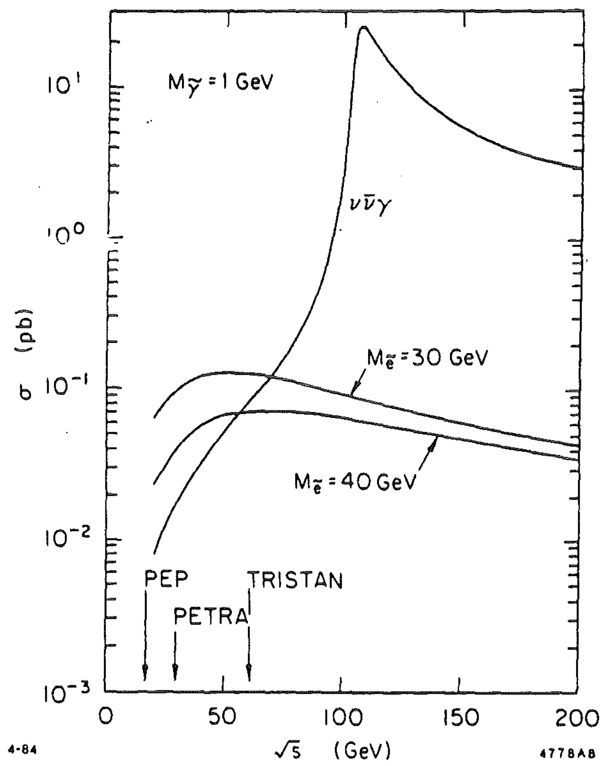


Fig. 13

Energy dependence of the reactions $e^+e^- \to \tilde{\gamma}\tilde{\gamma}\gamma$ and $e^+e^- \to \nu\bar{\nu}\gamma$.

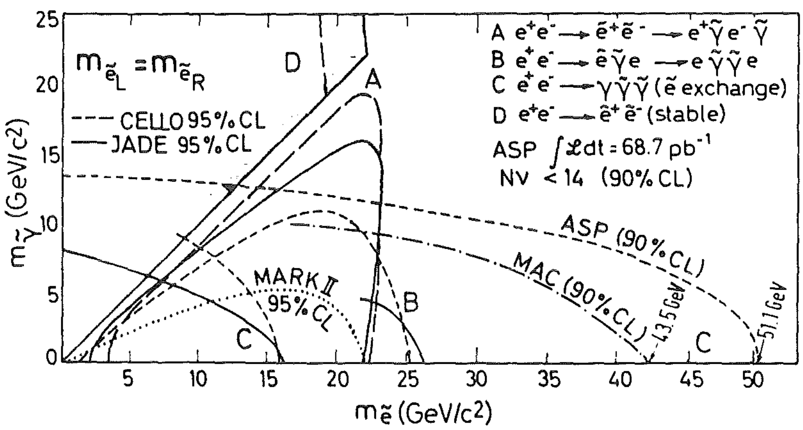


Fig. 14 Experimental limits on the $\tilde{\gamma}$ and $\tilde{e}$ masses from the reactions of Fig. 12a,b,c.

14 summarizes the most important results from ASP[33], CELLO[34], JADE[35], and MAC[46]. Note in particular, that the ASP result based on an integrated luminosity of 68.7 pb^{-1} could push the $\tilde{e}$ mass limit for massless $\tilde{\gamma}$ to

$$M_{\tilde{e}} > 51.1 \text{ GeV } (90\% \text{ C.L.}).$$

The result can also be expressed as a limit on the number of neutrinos

$$N_{\nu} < 14 \quad (90\% \text{ C.L.}).$$

If the photino is massive with a mass larger than the Goldstino (gravitino) it is unstable and decays into a photon and a Goldstino (or gravitino) $\tilde{G}$ (c.f. Fig. 15). The photino lifetime is then given by $\tau_{\tilde{\gamma}} = 8 \pi d^2/M^5_{\tilde{\gamma}}$, where d is the scale parameter of SUSY breaking[37]. The experimental signatures are illustrated in Fig. 15a,b, and c. Two relatively heavy photinos decaying in the detector give rise to two acoplanar photons (c) whereas relatively light photinos would reveal themselves by large missing energy of the two decay photons (a). Both cases were first studied by the CELLO group[38] and later by the JADE[39], MARK J[40], and TASSO[41] collaborations. The JADE group also investigated case (b) where only one photino decays in the detector, whereas the other one escapes, thus leaving a single photon in the detector. The results of all four PETRA experiments are summarized in Fig. 16. One can see that $\tilde{\gamma}$ decay is excluded for $M_{\tilde{e}} \lesssim 100$ GeV and $M_{\tilde{\gamma}} \lesssim 20$ GeV.

5b. Monojets and Searches for Neutralinos, Neutral Higgs and Gluinos

As mentioned above, photinos, zinos, and shiggs may mix to form neutralinos[6]. In particular, a light $\tilde{\chi}^0_1$ and an unstable $\tilde{\chi}^0_2$ may result from such a mixing. $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$ could be produced in pairs where $\tilde{\chi}^0_2$ would decay into a pair of fermions and a $\tilde{\chi}^0_1$ (Fig. 17a,b).

These ideas and the search for such phenomena got a considerable new impact by the observation of 'monojets' in the UA1 collaboration[42]. Many

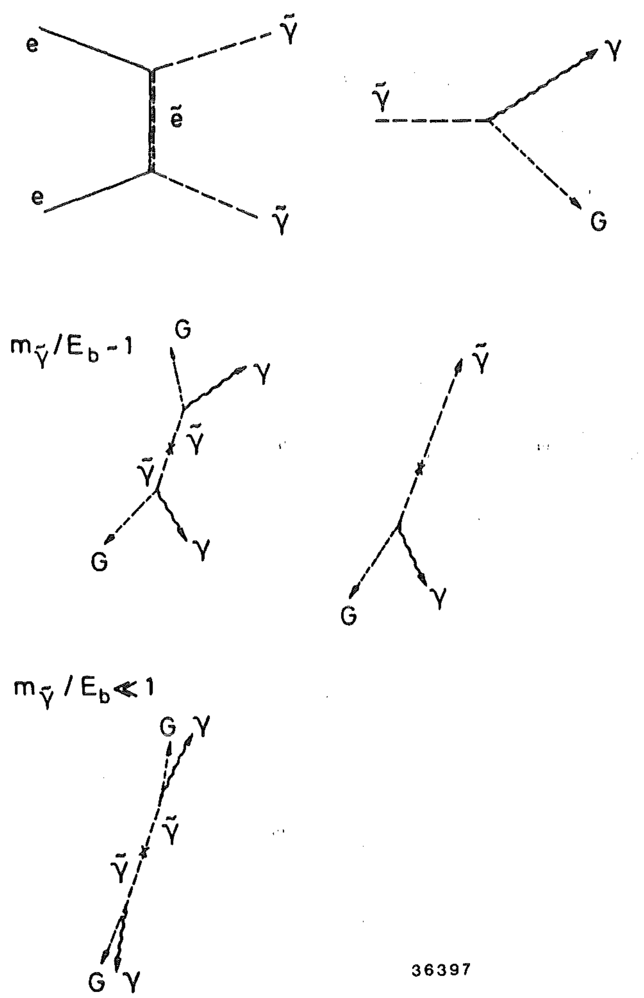


Fig. 15 Production and decay of photinos in e^+e^- annihilation and expected event topologies (G = Goldstino).

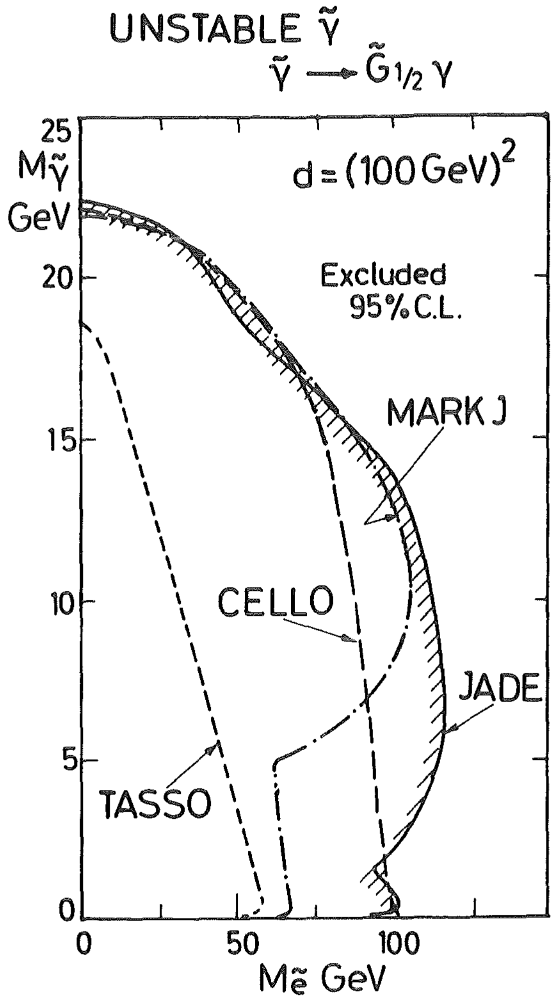


Fig. 16
Experimental limits on the masses of $\tilde{e}$ and $\tilde{\gamma}$ for the case that $\tilde{\gamma}$ decays into $\gamma + \tilde{G}$.

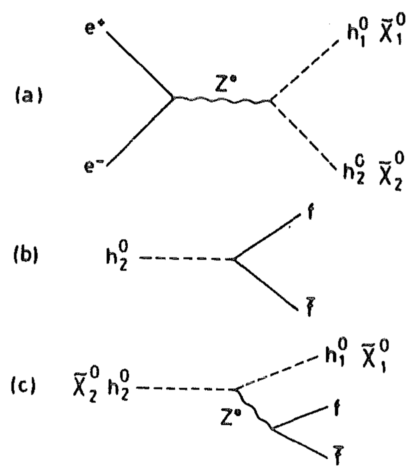


Fig. 17
Production and decay of neutral particles in e^+e^- annihilation
a) Production of neutralinos $\tilde{\chi}^0$ and neutral Higgs h^0.
b) Decay of the h_2^0 into heavy fermions
c) Decay of the heavier partners $\tilde{\chi}_2^0$ or h_2^0 into the light partners $\tilde{\chi}_1^0$ or h_2^0

explanations were suggested for these single jets with large missing $p_\perp$ including

$$Z^0 \rightarrow 2 \text{ heavy Neutralinos } \tilde{\chi}_1^0 \, \tilde{\chi}_2^0 \quad {}^{43}$$
$$Z^0 \rightarrow 2 \text{ neutral Higgs } h_1^0 \, h_2^0 \quad {}^{44} \qquad (13)$$

Others suggested that gluinos and squarks may be the source of monojets[45].

Although the UA1 data seem to have found a conventional explanation meanwhile[46], they initiated several searches in e^+e^- annihilation which are important in their own right. I will first discuss the Z^0 decays (13) and then the search for gluinos.

Neutralinos and Neutral Higgs

The suggested neutral particles (13) would couple to the virtual Z^0's produced at PEP and PETRA (Fig. 17a). In case of the neutralinos $\tilde{\chi}^0$ and neutral Higgs h^0 the light partner $\tilde{\chi}_1^0$ or h_1^0 is assumed to escape the detector. The heavier partners $\tilde{\chi}_2^0$ or h_2^0 will decay into the light $\tilde{\chi}_1^0$ or h_1^0 according to the diagram of Fig. 17c. The h_2^0 could also couple directly to a pair of heavy fermions, preferentially τ, c, b (Fig. 17b). There are the following free paramters in the game

$$\tilde{\xi} = \frac{\Gamma(Z^0 \rightarrow \tilde{\chi}_1^0 \, \tilde{\chi}_2^0)}{\Gamma(Z^0 \rightarrow \nu\bar{\nu})} \quad \text{or} \quad \xi = \frac{\Gamma(Z^0 \rightarrow h_1^0 \, h_2^0)}{\Gamma(Z^0 \rightarrow \nu\bar{\nu})}$$

which control the production rate and $r = BR(h_2^0 \rightarrow f\bar{f})$ to define the relative importance of the decays of Diagram 17b and c.

The experimental limits obtained by different groups at PEP[47,48,49] and PETRA[50,51] are summarized in Figs. 18 and 19 for the case of neutralinos and neutral Higgs particles. Note that the specific model of

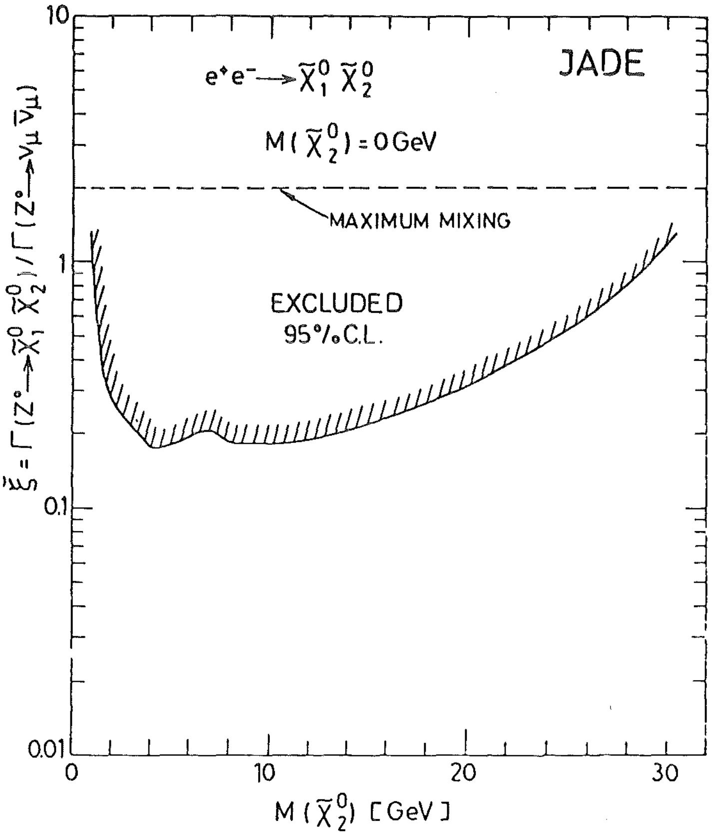
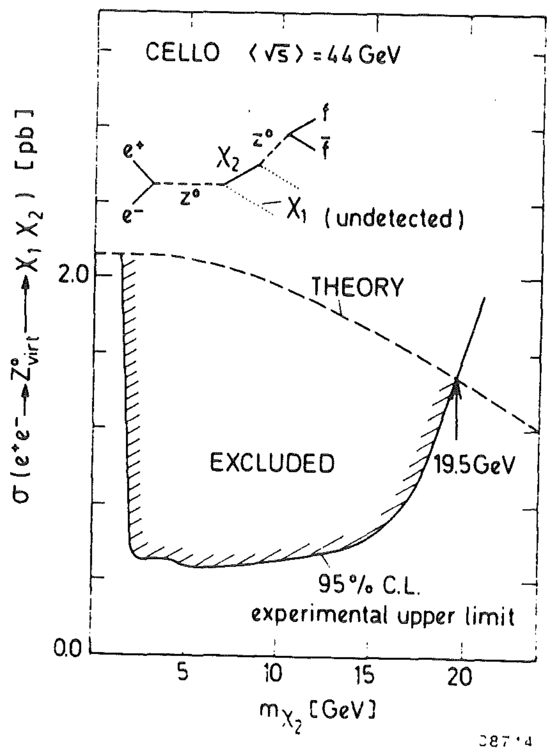


Fig. 18
Experimental limits on the mass of a hypothetical heavy neutralino $\tilde{\chi}^0_2$

a) as a function of the relative decay width $\tilde{\xi}$



b) for fermionic decay

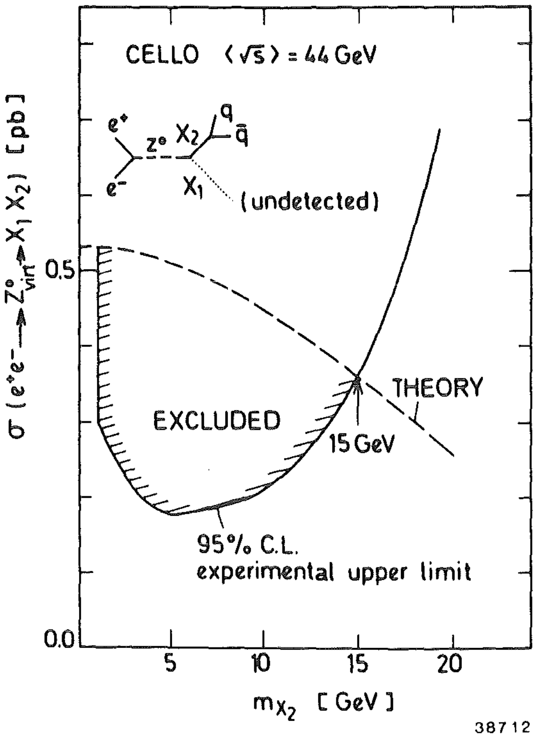


Fig. 18

Experimental limits on the mass of a hypothetical heavy neutralino $\tilde{\chi}_2^0$

c) for hadronic decay.

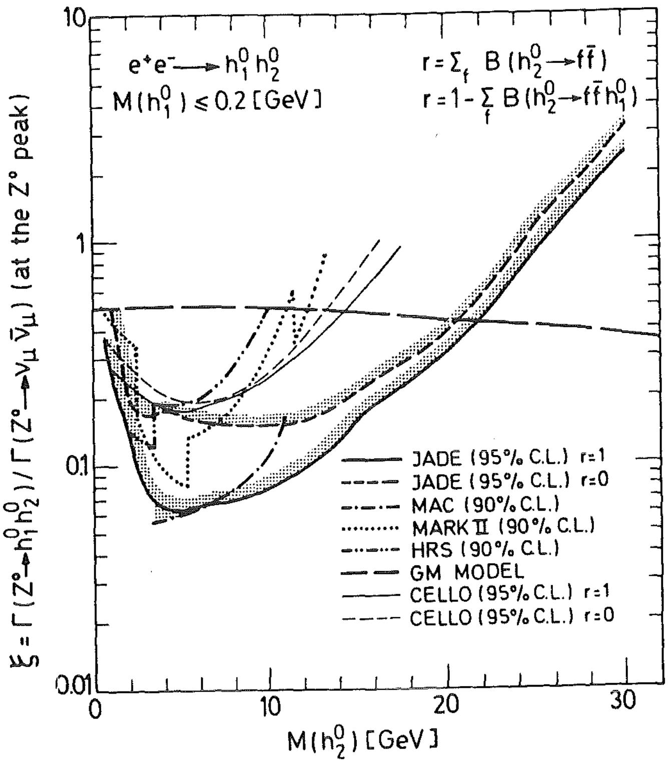


Fig. 19

Experimental limits on the mass of a hypothetical neutral Higgs h_2^0 as a function of the relative decay width ξ. The dashed line is the prediction of the model of Glashow and Manohar.

Glashow and Manohar[44] which attempted to explain the UA1 monojets is excluded for masses 2 GeV $\lesssim M_{h_2^0} \lesssim$ 20 GeV. This rules out neutral Higgs particles as source of the UA1 monojets which occur in the mass range between 3 and 15 GeV.

Gluinos

In radiative Υ transistions, the decay of the $\chi_b(^3P_1)$ state into two massless gluons is suppressed due to helicity arguments. Therefore, the decay into one massless and one virtual massive gluon g^* becomes dominant. g^* will couple either to a $q\bar{q}$ pair or to a pair of gluinos as indicated in Fig. 20a. If the gluino is relatively light, this mode could have a sizable branching ratio. The gluino would decay into a quark pair and a photino (Fig. 20b) with a lifetime[52]

$$\tau(\tilde{g}) \approx 1.3 \times 10^{-11} \left(\frac{M_{\tilde{q}}}{100\text{ GeV}}\right)^4 \left(\frac{1\text{ GeV}}{M_{\tilde{g}}}\right)^5$$

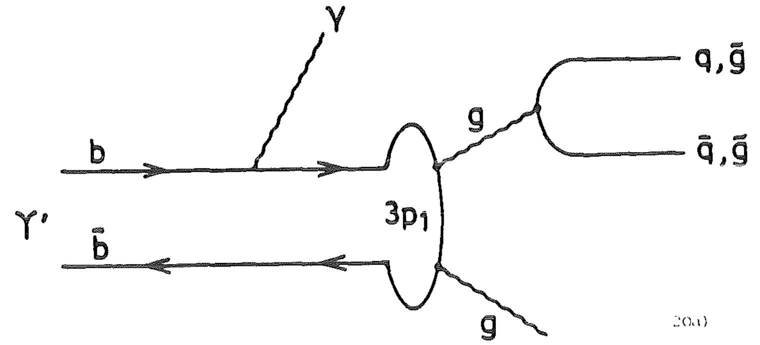
For gluino masses of the order of some GeV and very heavy squark masses (some 100 GeV) the lifetime would be long enough to be detectable.

The ARGUS collaboration searched for secondary vertices in their $\Upsilon(2S) \rightarrow \tilde{\chi}_b\,(^3P_1) + \gamma$ events[53]. The experimental limits they can deduce are given in Fig. 21 together with other limits on gluino and squark masses[54].

6. SEARCH FOR COMPOSITENESS

6a Excited Leptons

If leptons were composite particles, one would expect to observe finite structures and excited states. As far as structures are concerned, no deviation from pointlike behaviour of e, μ, and τ has been observed up to O (100 GeV)$^{-1}$.



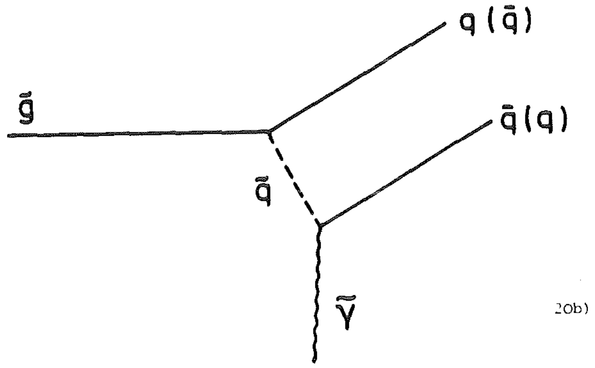


Fig. 20a Radiative decay of the γ through the $\chi_b(^3P_1)$ state.

The decay into 2 massless gluons is suppressed.

20b Decay of a gluino.

There are two reactions through which excited leptons (heavier particles with the same quantum numbers as the corresponding leptons) could be produced directly in e^+e^- annihilation (Fig. 22a,b)

$$e^+e^- \rightarrow \ell^* \ell^* \tag{14}$$

$$e^+e^- \rightarrow \ell^* \ell . \tag{15}$$

Whereas the cross section for (14) in the case of a pointlike ℓ^* with a mass less than the beam energy would be given by (1), reaction (15) would require an unconventional current Lagrangian[55]

$$L = \frac{e\lambda}{2M_{\ell^*}} \bar{\ell}^* \sigma_{\mu\nu} \ell F^{\mu\nu} + \text{h.c.}$$

where λ is the coupling strength which is unknown.

ℓ^* decays rapidly

$$\mu^* \rightarrow \mu + \gamma$$

and one observes a signal

$$e^+e^- \rightarrow \mu^+\mu^-\gamma(\gamma) \tag{16}$$

which has to be separated from the radiative QED background. Mass limits on M_{μ^*} are of course restricted to less than the beam energy in reaction (14), whereas high values ($\leqslant \sqrt{s}$) can be reached in reaction (15).

Searches for excited leptons ℓ^* have been performed by the CELLO[56], JADE[57], MARK J[58], and MAC[59] collaborations. For masses below beam energy, mass limits can be deduced from the observed limits on excess events of type (16) compared to the expected cross section (1). Recent values are given in Table 3. In the case of reaction (15), an excited muon would show up as a peak in the invariant mass distribution of the $\mu\gamma$ system. No such signal has been observed. From a comparison with the QED predic-

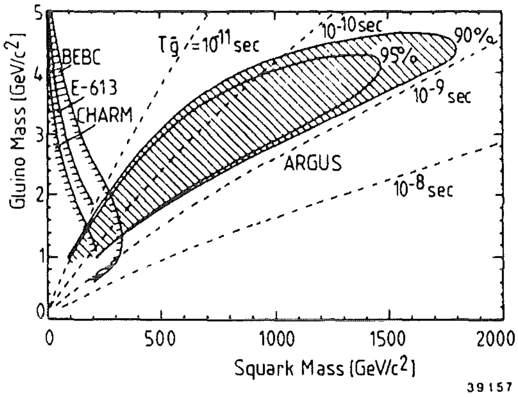


Fig. 21

Experimental limits on the gluino and squark masses.

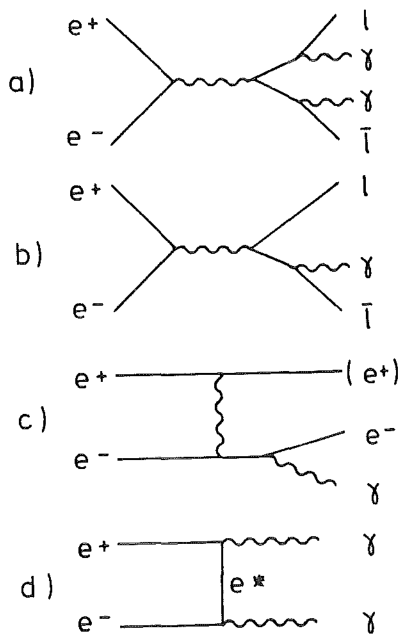


Fig. 22

Production of excited leptons

a) $e^+e^- \rightarrow \ell^* + \ell^*$

b) $e^+e^- \rightarrow \ell^* + \ell$

c) 'virtual compton' process

d) e* exchange in e^+e^- $\rightarrow \gamma\gamma$.

tion, upper limits on the observed cross section for reaction (15) can be obtained. By means of the expected cross section this can be transformed into limits on the coupling constant λ as a function of M_{μ^*}. Fig. 23 shows recent results from the CELLO and JADE collaborations. For $\lambda = 1$ mass limits can be pushed as high as 40 GeV. However, parametrizing the coupling by $(M_{\ell^*}/\Lambda^2)^2$ instead of $(\lambda/M_{\ell^*})^2$ with the compositeness scale Λ would be an equally good choice. In this case, for reasonable values of $\Lambda \simeq 1$ TeV[60] the result of Fig. 23 does not give any further restriction on the ℓ^* mass which would exceed the values of Table 3.

TABLE 3: Mass limits in GeV on excited leptons (95% C.L., form factor F = 1)

	e^*	μ^*	τ^*
JADE	23.1		22.5
CELLO	23.0	22.6	22.5

In case of excited electrons, limits can be pushed further by investigating the 'virtuel compton' graph of Fig. 22c[61] and a hypothetical e^* exchange in $e^+e^- \rightarrow \gamma\gamma$ (Fig. 22d). The latest results on these processes from the CELLO[56] and JADE[57] groups are given in Fig. 24. Again, assuming $\lambda = 1$ the mass limit could be pushed as high as 84 GeV whereas for $\Lambda \simeq 1$ TeV only the pair production limit of Table 3 holds.

6b. The CELLO Event and Search for Leptoquarks

In search of isolated muons in hadronic e^+e^- annihilation the CELLO collaboration found an event of the type

$$e^+e^- \rightarrow \mu^+\mu^- \text{ jet jet}$$

with large transverse momentum of the muons with respect to the event axis[62]. The probability to find such events from conventional sources (mainly α^4-QED) was estimated to be of the order of 10^{-3}.

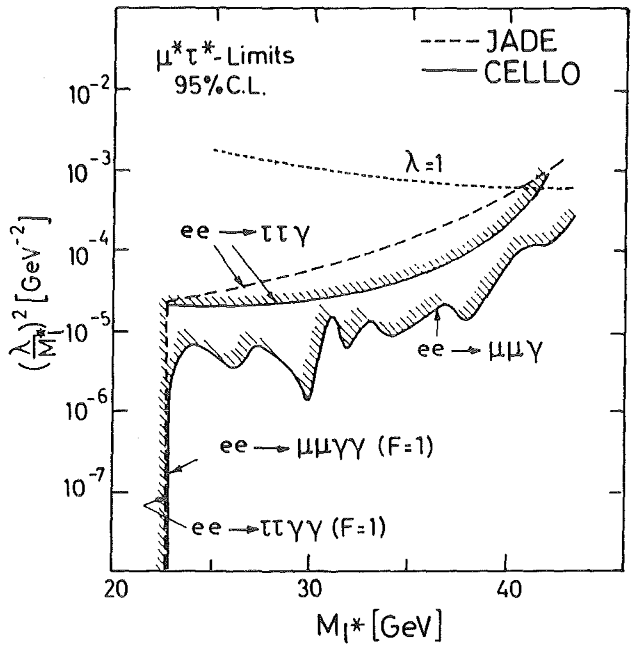


Fig. 23
Experimental limits on the production of excited muons and taus as a function of the mass and the coupling strength $(\lambda/M_{\ell*})^2$. An equally good parametrization would be $(M_{\ell*}/\Lambda^2)^2$.

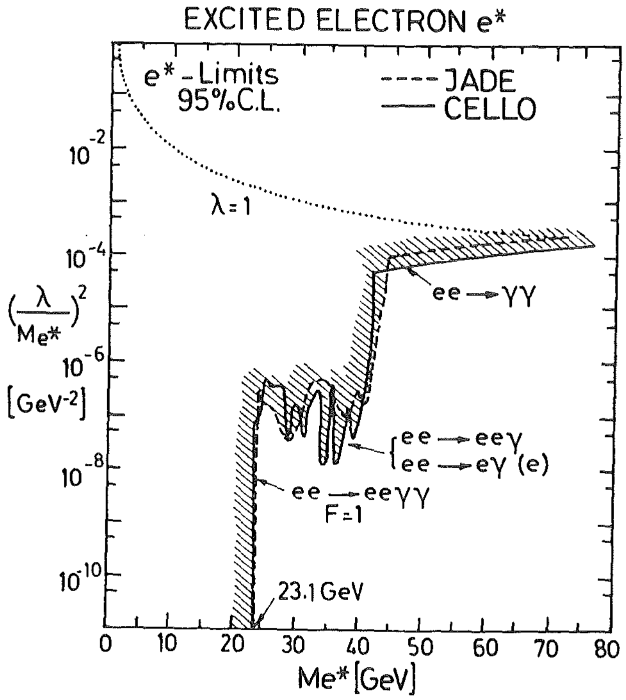


Fig. 24
The same as Fig. 23 for excited electrons.

Two events of similar topology have been seen at the UA1 detector[63] and B. + F. Schrempp[64] realized, that the symmetric solution of μ-jet masses of all three events clustered around 20 GeV (Fig. 25). They suggested, that the events may be due to pairproduction and decay of leptoquarks χ^{μ} of the second generation. They argue that in composite models one light leptoquark may exist for each generation: χ^{e}, χ^{μ} and χ^{τ}. Each χ would have quark-antilepton quantum numbers, i.e. charge 2/3 and spin 0. The second generation χ^{μ} would decay

$$\chi^{\mu} \rightarrow s\mu^{+},\ c\bar{\nu}_{\mu}$$

Thus not only $\mu\mu$ jet jet but also $\mu\nu$ jet jet and $\nu\nu$ jet jet events are expected. The JADE collaboration performed a systematic search for all three categories[65]. They found only one candidate in the $\mu\mu$ jet jet class, however with low invariant μ jet masses. Fig. 26 shows the mass ranges excluded by their search for the different event classes. It excludes light leptoquarks between 4 and 20.8 GeV at the 95% C.L. The CELLO event sits right at the edge of their contour.

7. CONCLUSION

- No evidence for new particles has been found at PEP/PETRA/DORIS II/CESR.
- Some puzzling phenomena like the CELLO event $e^{+}e^{-} \rightarrow \mu^{+}\mu^{-}$ jet jet or the broad events with high transverse momentum muons in the MARK J detector still remain unexplained.
- Let us wait for and look forward to the next generation of $e^{+}e^{-}$ machines TRISTAN, SLC, LEP!

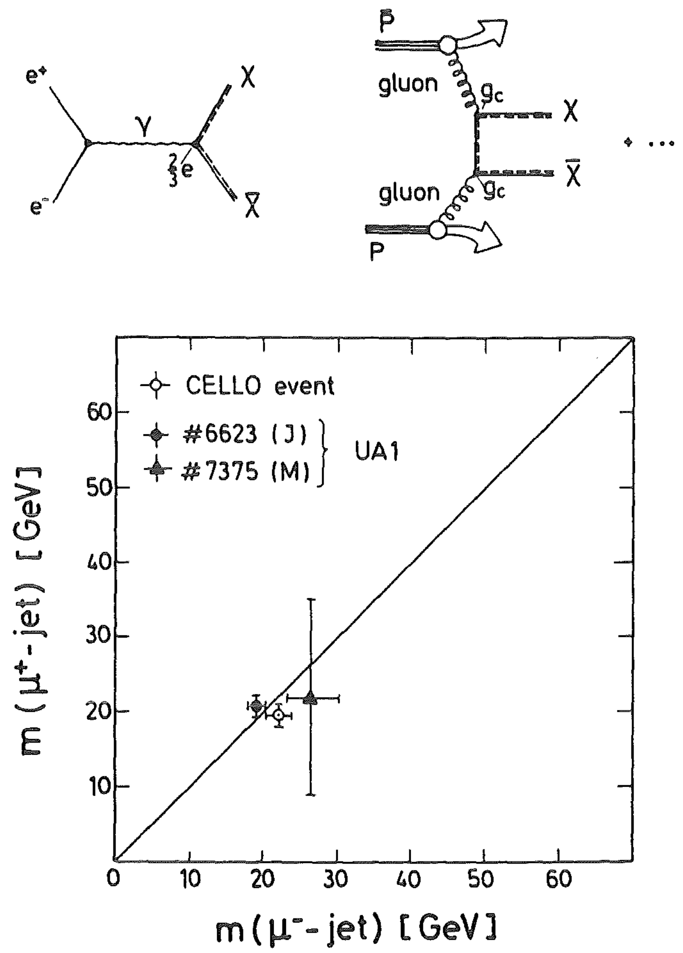


Fig. 25
Leptoquarks in (a) e^+e^- and (b) $\bar{p}p$ annihilation. Symmetric solution of the μ-jet masses in the CELLO and UA1 $\mu^+\mu^-$ jet jet events.

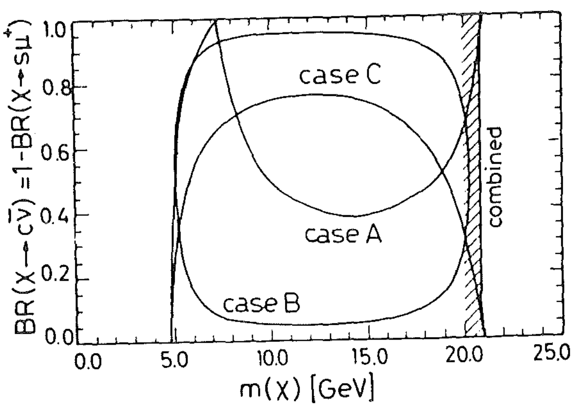


Fig. 26
Experimental mass limits on leptoquarks as a function of the branching ratio $\chi^{\mu} \rightarrow c\bar{\nu}_{\mu}$.

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