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

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ABSTRACT

Extensive searches for new particles have been performed at e^+e^- storage rings. No new leptons or quark flavours have been found up to centre of mass energies of 36.75 GeV. Also the search for new scalars has been negative. In particular, supersymmetric leptons must have masses larger than 16 GeV and charged technipions and "standard" axions can be excluded.

SUCHE NACH NEUEN TEILCHEN IN e^+e^- ANNIHILATION

ZUSAMMENFASSUNG

Eine umfassende Suche nach neuen Teilchen ist an e^+e^- Speicherringen durchgeführt worden. Bis zu Schwerpunktsenergien von 36.75 GeV wurden keine neuen Leptonen oder Quarks gefunden. Auch die Suche nach neuen skalaren Teilchen blieb ergebnislos. Insbesondere müssen supersymmetrische Leptonen Massen von mehr als 16 GeV haben und können geladene Technipionen und "Standard"-Axionen ausgeschlossen werden.

Talk at the DESY Workshop 1982; Electroweak Interactions at High Energies, September 28-30, 1982

1. Introduction

As the title indicates, this is a report on the discoveries which have not (yet) been made at e^+e^- storage rings. Motivations to search for new particles come from many sources. Even in the "standard" GWS-GIM-model[1,2] several particles are still missing. Numerous alternatives and extension to this model call for a large variety of other or additional particles:

- Fermions

  Besides the top quark and the τ neutrino, for which direct evidence is still missing, further families of quarks and leptons (sequential leptons) may still exist. More exotic leptons (stable, excited, or neutral) are predicted in specific models and fractional charged quarks (and monopoles) are under heated discussion again. Moreover, supersymmetric theories predict spin 0 partners of quarks and leptons (squarks, sleptons).

- Vector Bosons

  The mediators of the weak interaction, $W^{\pm}$ and Z^o, are not the only particles on the shopping list for new vector bosons. Again, in particular supersymmetry, predicts fermion partners. Some of them, photinos and gravitinos, will be discussed.

- Scalar Bosons

  Whereas the standard model asks for one single physical scalar (Higgs) boson H^o, also charged Higgses, axions and technipions are predicted in other models.

Many of the new particles suggested above are directly or indirectly accessible in e^+e^- reactions. In e^+e^- annihilation the direct production of charged (e_q), pointlike particles is given by ($\beta = v/c$, s = centre of mass energy squared, $\sigma_{QED} = 4\pi\alpha^2/3s$

$$\sigma = \sigma_{QED} \cdot e_q^2 \frac{\beta(3-\beta^2)}{2} \qquad \text{spin } 1/2 \qquad (1)$$

$$\sigma = \sigma_{QED} \cdot e_q^2 \; 1/4 \; \beta^3 \qquad \text{spin } 0 \qquad (2)$$

i.e. the production of scalars is 4 times smaller and suppressed by an additional threshold factor with respect to the production of spin 1/2 fermions (see Fig. 1). We will start with the discussion of fermions and then proceed to scalar particles.

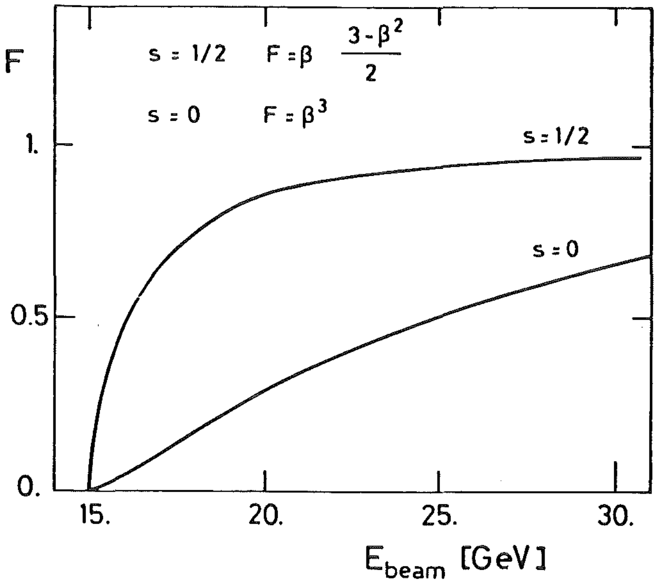


Fig. 1

Threshold behaviour of pointlike scalars and spin 1/2 fermions in e^+e^- annihilation[3c]

This report will include searches carried out by the MAC, MARK II, PEP12 and PEP14 experiments at PEP, the CELLO, JADE, MARK J, PLUTO, and TASSO experiments at PETRA, the CLEO and CUSB experiments at CESR, and the Crystal Ball and MARK II experiments at SPEAR. Similar reports have been published previously[3].

2. Search for New Fermions

2.1 The "Old" Sequential Heavy Lepton τ

Before we talk about new lepton families, let us first have a quick look at the last one[4].

The τ lepton has so far not shown any deviation from the straightforward predictions for a sequential heavy lepton. Latest results from high energies show pointlike behaviour

$$\sigma_{\tau\tau} = \sigma_{QED}\,(1.03 \pm 0.05 \pm 0.07) \qquad \text{CELLO}^{5)}$$

$$\sigma_{\tau\tau} = \sigma_{QED}\,(0.97 \pm 0.05 \pm 0.06) \qquad \text{MARK II}^{6)}$$

and a charge asymmetry in the angular distribution

$$A = -8.0 \pm 2.3 \qquad \text{PETRA average}^{7)}$$

in good agreement with the prediction of the standard model

$$A = -9.3 \pm 0.2 \qquad \text{Theory} \cdot$$

As reported in Paris, several groups have now been able to measure the lifetime of the τ lepton. In particular, the beautiful measurement of the MARK II group yields

$$\tau_\tau = (3.31 \pm 0.57 \pm 0.6) \cdot 10^{-13}\,\text{s} \qquad \text{MARK II}^{8)}$$

in agreement with the value expected from e-μ-τ universality

$$\tau_\tau = (2.8 \pm 0.2) \cdot 10^{-13}\ \text{s} \qquad \text{Theory} \cdot$$

Apart from the value this measurement has in itself, it bears heavily on the question of whether or not the τ neutrino exists[4b)].

Already before the new measurements on the τ lifetime were performed in 1982, it was known that an extra neutrino was involved in τ decays and that this neutrino was different from ν_μ, $\bar{\nu}_\mu$ and $\bar{\nu}_e$[4c)]. However, the one case $\nu_\tau = \nu_e$ could not be excluded. Now, arguments similar to those which already led to the exclusion of $\nu_\tau = \nu_\mu$ can also be applied for ν_e.

Let us consider the coupling strength $\varepsilon(\tau - \nu_e)$ of a hypothetical τ-ν_e vertex. If $\varepsilon(\tau\text{-}\nu_e) \neq 0$, this would lead to a production of τ's in ν_e interactions. In a beam dump experiment, the BEBC group has determined an upper limit$^{9)}$

$$\varepsilon(\tau\text{-}\nu_e) \; < \; 0.35 \text{ of universal coupling strength} \quad (90\% \text{ C.L.})$$

from the comparison of charged/neutral current ν_e interactions. On the other hand, the MARK II lifetime value constrains the value from below

$$\varepsilon(\tau\text{-}\nu_e) \; > \; 0.75 \text{ of universal coupling strength} \quad (90\% \text{ C.L.}) \quad .$$

This contradiction indicates that ν_τ cannot be identical to ν_e. Thus, by exclusion of all alternatives, we have indirect experimental evidence for a new neutrino ν_τ in τ decays.

2.2 The Next Sequential Heavy Lepton L

The production and decay of a hypothetical new heavy lepton L is shown in Figs. 2a and b. As an example the predicted branching ratios for a mass of 16 GeV are given in Table 1 $^{10)}$. The signatures which can be used are similar to those for τ detection (Figs. 2c,d,e). Signature (c) - a μ acoplanar with a jet of invariant mass larger than the τ mass - has been used by most groups to search for a new lepton. Signature (d) - two acoplanar jets of invariant mass larger than the τ mass - has been used by JADE, the signature (e) -acoplanar e μ pair -

Table 1: Branching ratios for a hypothetical sequential heavy lepton L^- of mass M_L = 16 GeV $^{10)}$

$$BR(L \to \ell\nu\nu) \; \simeq \; 10.7\% \quad (\ell = e,\mu,\tau)$$

$$BR(L \to \nu\bar{u}d) \; \simeq \; BR(L \to \nu\bar{c}s) \; \simeq \; 32\%$$

$$BR(L \to \nu\bar{u}s) \; \simeq \; BR(L \to \nu\bar{c}d) \; \simeq \; 2\%$$

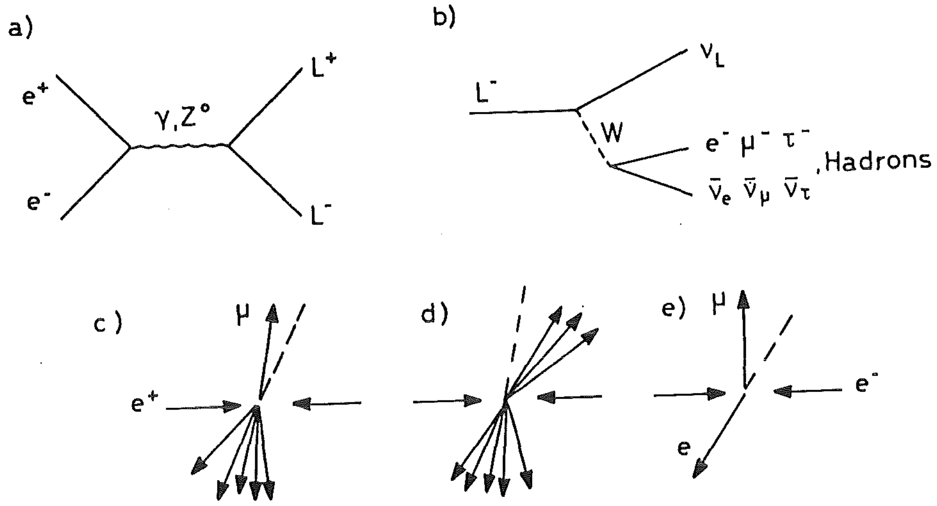


Fig. 2: Production (a) and decay (b) of sequential heavy leptons and different experimental signatures (c,d,e).

by the MARK II group. The results are summarized in Table 2.

Table 2: Experimental lower limits (95% C.L.) on the mass M_L of a new sequential heavy lepton L

experiment	mass limit	Ref.
CELLO	$M_L > 16.3$ GeV	11
JADE	$M_L > 18.1$ GeV	3a
MAC	$M_L > 14.5$ GeV	12,13
MARK J	$M_L > 16.0$ GeV	14
MARK II	$M_L > 13.8$ GeV	12
PLUTO	$M_L > 14.5$ GeV	15
TASSO	$M_L > 15.5$ GeV	16

The cases of ortho ($\nu_L = \nu_e, \nu_\mu, \nu_\tau$) or para ($\nu_L = \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$) leptons have not been evaluated in detail, but would lead to similar limits.

2.3 Stable Charged and Heavy Neutral Leptons

New lepton families may exist, in which the neutral partner is heavier than the charged one 17):

$$\begin{pmatrix} L^0 \\ L^- \end{pmatrix} \quad \text{with} \quad M_{L^0} > M_{L^-} \qquad (3)$$

This would lead to lepton signatures much different from the sequential case discussed above.

Stable Charged Leptons

If the new lepton family has its own conserved quantum number, the charged partners are stable and behave like additional "μ pairs" with low momenta

$$e^+e^- \rightarrow L^+L^- \qquad L^\pm \text{ stable} \qquad (4)$$

The MARK J and JADE groups have searched for such signals. Fig. 3

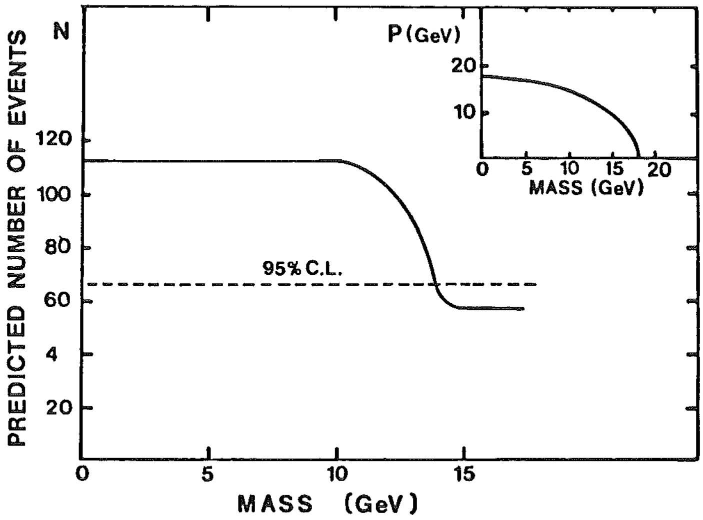


Fig. 3

Experimental limit on the production of stable charged leptons (MARK J) 19) shows the upper limit deduced from μ pair production in MARK J compared to the expected number of events. The JADE group has looked for excessive stable charged particle pair production (see below). The experimental limits of the two groups are (95% C.L.)

$M_{L^\pm} > 12$ GeV (for charges $\geq 2/3$) JADE [18)]

$M_{L^\pm} > 14$ GeV MARK J [19)]

It should be kept in mind that these limits only hold for $M_{L^0} > M_{L^-}$ [4a)]. If both masses would be similar with the charged lepton slightly heavier, L^- decays of the type

$$L^- \rightarrow L^0 + e^- + \bar{\nu}_e \quad \text{etc.} \qquad (5)$$

would be very difficult to detect. Because of the low electron energy and large missing mass they would probably be indistinguishible from 2γ events.

Neutral Heavy Leptons

For the heavy neutral lepton in a hypothetical new family the following phenomenlogical cases have to be considered ($\ell = e,\mu,\tau$) (Ref. 4a)

- New conserved lepton number, charged (L^-) or neutral (ν_L) partner

$$L^0 \rightarrow \nu_L + \ell^+ + \ell^- \quad \text{or} \quad \nu_L + \text{hadrons}^0 \qquad (6a)$$

$$L^0 \rightarrow L^- + \ell^+ + \nu_\ell \quad \text{or} \quad L^- + \text{hadrons}^+ \qquad (6b)$$

- No new conserved lepton number, "old" lepton partners (ℓ^-, ν_ℓ)

$$L^0 \rightarrow \nu_\ell + \ell^+ + \ell^- \quad \text{or} \quad \nu_\ell + \text{hadrons}^0 \qquad (6c)$$

$$L^o \rightarrow \ell^- + \nu_\ell + \ell^+ \quad \text{or} \quad \underline{\overline{\ell^- + \text{hadrons}^+}} \qquad (6d)$$

Since the production of L^o can only occur through weak interactions (Fig. 4), cross sections will be low. The cross section of pair production via Z^o (Fig. 4a) is estimated to be of the order of$^{20)}$

$$\sigma(e^+e^- \rightarrow L^o\overline{L^o}) \simeq 0.016 \cdot \sigma_{QED} \qquad (\sqrt{s} = 40 \text{ GeV})$$

at PEP/PETRA energies, corresponding to about 60 events/100 pb^{-1}. Note that the cross section ratio increases like $\sigma/\sigma_{QED} \sim s^2$.

For the particular case of ℓ being an electron in (6d), the heavy neutral electron E^o can also be produced via $W^\pm$ exchange (Fig. 4b) with a substantially higher cross section

$$\sigma(e^+e^- \rightarrow \bar{E}^o\ \nu_e) \simeq 0.1\ \sigma_{QED}$$

at PEP/PETRA energies. This possibility has been studied by the JADE group$^{3a,c)}$ for the case, where E^o decays into an electron and hadrons. The experimental signature and the expected cross section are given in Fig. 5. No event has been observed, which corresponds to the following 95% C.L. lower limits on the mass of E^o in case of V+A or V-A interaction$^{21)}$.

$M(E^o) > 24.5$ GeV (V+A) JADE

$M(E^o) > 22.5$ GeV (V-A) JADE

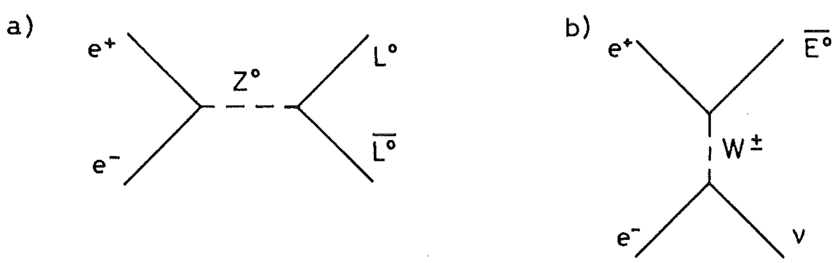
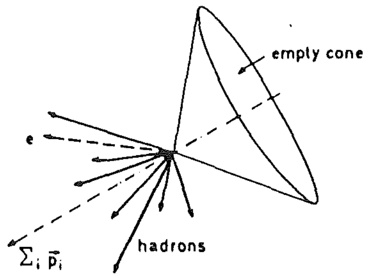


Fig. 4

Production of neutral leptons in e^+e^- annihilation



Event signature for neutral heavy electron

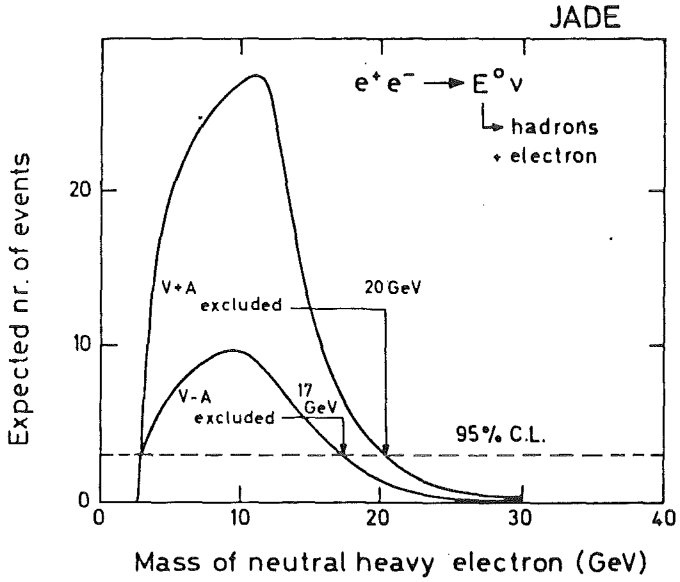


Fig. 5

Experimental limits on the production of neutral electrons (JADE) (Ref. 3a)

2.4 Excited Charged 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 $(100\ \mathrm{GeV})^{-1}$.

Direct Production of μ^*

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. 6)

$$e^+e^- \to \mu^*\mu^* \qquad (7)$$

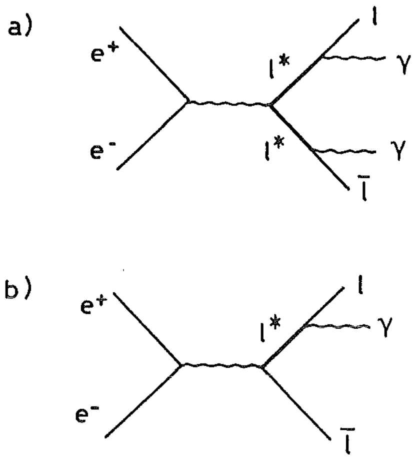


Fig. 6

Production of excited charged leptons

$$e^+e^- \rightarrow \mu^*\mu \qquad (8)$$

Whereas the cross section for (7) in the case of a pointlike μ^* with a mass less than the beam energy would be given by (1), reaction (8) would require an unconventional current of the type[22)] (coupling strength λ)

$$e\lambda\ \psi_{\mu^*}\cdot\ \sigma_{\beta\alpha}\ \psi_{\mu} \qquad (9)$$

The cross section then reads (M_{μ^*} = mass of μ^*)

$$\sigma = \frac{8\pi\alpha^2}{3}\ \lambda^2\ (1-M^2_{\mu^*}/s)^2\ (1+2\ M^2_{\mu^*}/s) \qquad (10)$$

If μ^* decays rapidly

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

one would observe a signal

$$e^+e^- \rightarrow \mu^+\mu^-\gamma\ (\gamma) \qquad (11)$$

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 (7), whereas higher values ($\lesssim \sqrt{s}$) can be reached in reaction (8).

Searches for excited muons μ^* have been performed by the CELLO, JADE, MARK J, and MAC collaborations. For masses below beam energy, mass limits can be deduced from the observed limits on excess events of type (11) compared to the expected cross section (1). The experimental limits are summarized in Table 3.

Table 3: Experimental limits on μ^* masses from reaction $e^+e^- \to \mu^*\mu^*$

Experiment	Mass Limit (GeV) (95% C.L.)	Ref.
CELLO	> 16.9	11
JADE	> 10	3a
MARK J	> 10	19
MAC	> 14	12,13

In the case of reaction (8), an excited muon would show up as a peak in the invariant mass distribution of the $\mu\gamma$ system. As an example, the data of the MAC group[13)] are shown in Fig. 7. No such signal has been observed. From a comparison with the QED expectation, upper limits on the observed cross section for reaction (8) can be obtained. By means of the expected cross section (10) this can be transformed into limits on the coupling constant λ as a function of M_{μ^*}. Figs. 7 and 8 show two recent results from the MAC[13)] and MARK J[19)] groups. Similar limits were obtained by the CELLO and JADE collaborations[3b)]. Fig. 8 also shows the constraints on λ which can be obtained from the anomalous magnetic moment of the muon[23)].

At SPEAR the MARK II collaboration has also searched for signals of excited electrons and muons. They can put stringent limits on the production of e^* and μ^* up to masses of about 3 GeV. The results are shown in Fig. 9 [24)].

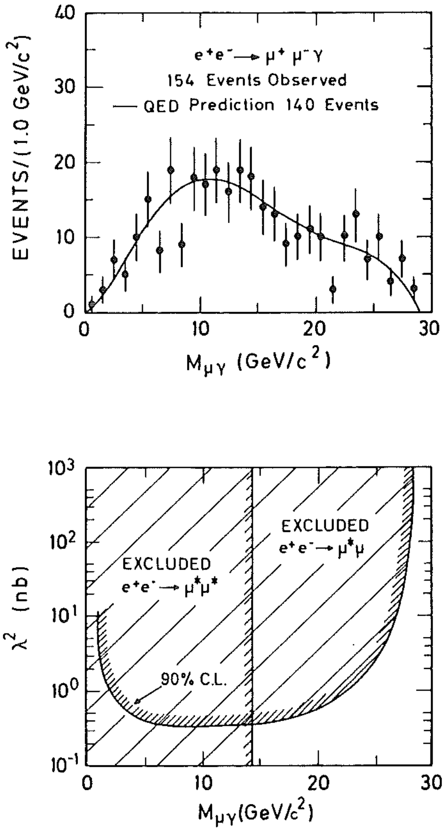


Fig. 7

Experimental limits on the production of excited muons μ^* (MAC)[13)]

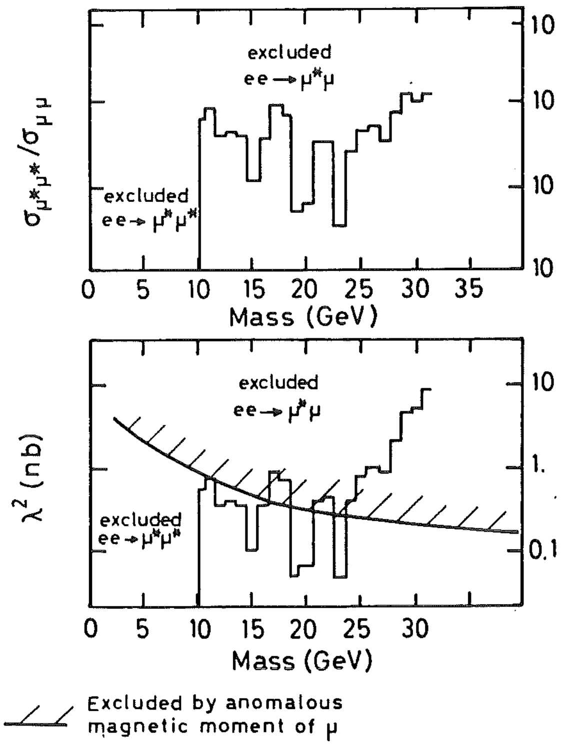


Fig. 8

Experimental limits on the production of excited muons μ^* (MARK J)[19)] together with limits from the anomalous magnetic moment of the muon[23)]

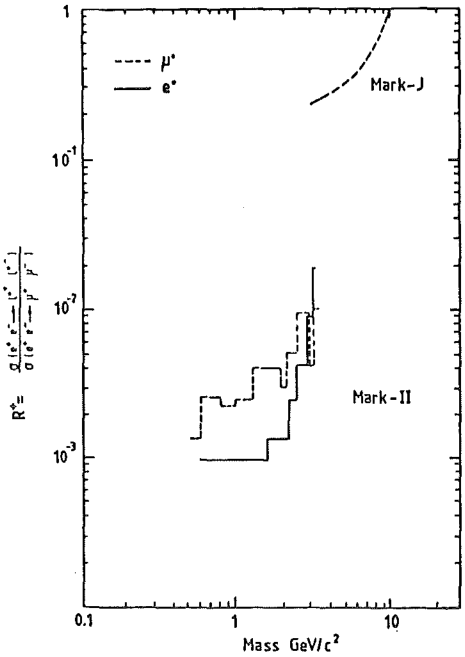


Fig. 9

Experimental limits on the production of excited muons μ^* and e^* (MARK II)[24]

Virtual Excited Electrons

If currents of the type (9) would exist, they would interfere with the electron exchange diagram of the reaction

$$e^+e^- \to \gamma\gamma \tag{12}$$

in the way indicated in Fig. 10. This modifies the cross section for (12)

$$\sigma = \sigma_{QED} \, (1 + (s^2/\Lambda^4) \sin^2\theta) \tag{13}$$

where $\Lambda = M_{e*} \sqrt{\lambda'}$ and λ' is the relative coupling strength of current (9).

Many groups have looked for deviations from QED in reaction (12) for which radiative corrections have been calculated up to $O(\alpha^3)$ and which is unaffected in lowest order by weak interactions. Figs. 11 and 12 show two recent results of the MARK II and CELLO collaborations. Both agree well with the QED predictions. According to (13) this can

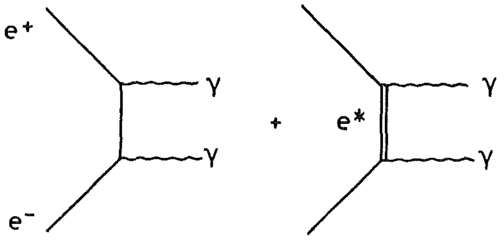


Fig. 10

Possible contributions to $e^+e^- \to \gamma\gamma$

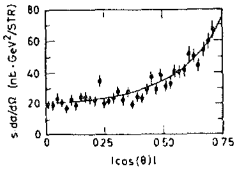


Fig. 11

Invariant differential cross section for the reaction $e^+e^- \to \gamma\gamma$. Data are compared to the QED prediction to O (α^3) (MARK II)[12)]

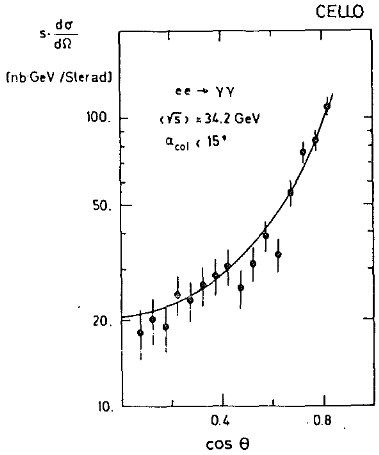


Fig. 12

Invariant differential cross section for the reaction $e^+e^- \to \gamma\gamma$. Data are corrected for radiative effects to O (α^3) and compared to lowest order QED (CELLO)[25)]

be transformed into a limit on $M_{e^*} \cdot \sqrt{\lambda'}$. Table 4 summarizes the results obtained by different groups at PEP and PETRA:

Table 4: Experimental Limits on $M_{e^*} \cdot \sqrt{\lambda'}$ (95% C.L.)

Experiment	$M_{e^*} \cdot \sqrt{\lambda'}$	Ref.
CELLO	> 59 GeV	25
JADE	> 47 GeV	26
MARK J	> 58 GeV	19, 27
MARK II	> 50 GeV	12
PLUTO	> 46 GeV	15,28
TASSO	> 34 GeV	29

2.5 Search for New Quark Flavours

One of the main objectives of the high energy e^+e^- machines is the search for new quark flavours. I will only very briefly sketch the extensive experimental program which has been carried out at highest PETRA energies to search for thresholds or resonances in the hadronic cross section[3a,b,c].

Search for Thresholds

Variations in the total cross section, event shapes and inclusive lepton rates would be indicative of new quark thresholds. No such changes have been observed up to center of mass energies of $\sqrt{s}$ = 36.75 GeV. This excludes new quark flavours with charge 2/3 (from total cross section) or 1/3 (from event shape analysis).

Search for Narrow Resonances

The highest energy region 33 GeV < $\sqrt{s}$ < 36.75 GeV has been scanned in steps of 20 MeV to look for narrow resonances. No resonances have been found. Quantitatively, an upper limit of

$$B_h \cdot \Gamma_{ee} < 0.65 \text{ keV} \quad (90\% \text{ C.L.})$$

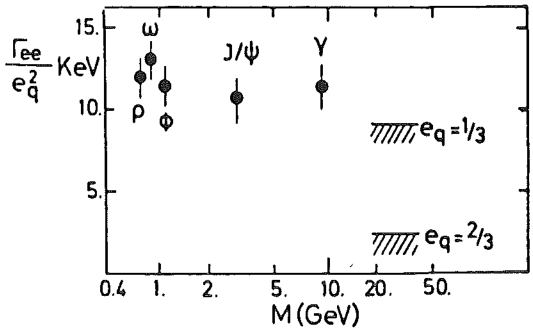


Fig. 13

The reduced leptonic width Γ_{ee}/q_e^2 of the known vector mesons compared to the experimental limit at highest PETRA energies[3c)]

can be deduced from the combined PETRA data where B_h is the hadronic branching ratio and Γ_{ee} the leptonic width of the resonance. If we assume $B_h = 0.7$ this gives an upper limit of

$$\Gamma_{ee} < 0.93 \text{ keV} \qquad (90\% \text{ C.L.})$$

In Fig. 13, this limit is compared to the width of known narrow vector mesons in terms of Γ_{ee}/e_q^2, e_q being the quark charge. If we assume Γ_{ee}/e_q^2 to be about constant, as previous data suggest, we can safely exclude a $t\bar{t}$ bound state with $e_t = 2/3$.

2.6 Search for Free Fractionally Charged Quarks

Searches for fractional charges have been performed in several experiments at PEP and PETRA. They all rely on a measurement in the specific ionisation

$$dE/dx \sim e_q^2 \cdot f(\beta) \quad . \tag{14}$$

The JADE group measures dE/dx and the reduced momentum p/e_q in a "jet" chamber[18)]. The PEP14 collaboration has no magnetic field and uses dE/dx and TOF measurements in scintillation counters[30,31)]. In addition, tracks are defined in proportional chambers. The MARK II group combines the dE/dx and TOF information from scintillation counters with a p/e_q measurement in the drift chambers[32)].

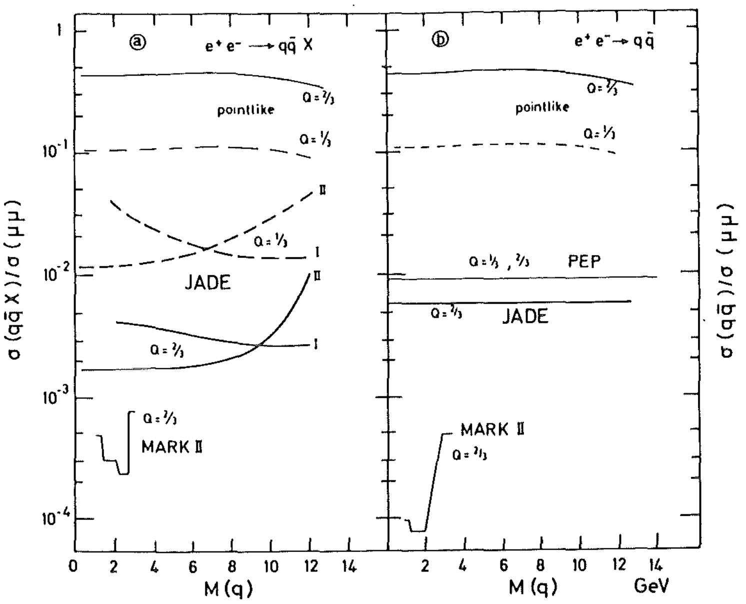


Fig. 14

Experimental upper limits on the cross section for inclusive and exclusive quark production as a function of the quark mass (JADE, MARK II, PEP14)[3a)]

(a) limits on inclusive production
(b) limits on exclusive production

All three groups have searched for the exclusive production of quarks

$$e^+e^- \rightarrow q\bar{q} \qquad (15)$$

JADE and MARK II have also determined limits on the inclusive production

$$e^+e^- \rightarrow q\bar{q}X \qquad (16)$$

No signals have been seen. The upper limits relative to the pointlike cross section $\sigma_{\mu\mu}$ as a function of the quark mass are shown in Fig. 14 (Ref. 3a).

2.7 Search for Monopoles

Monopoles (which, strictly speaking, do not fit in here, but are somewhat related to the question of fractional charges) were originally proposed by Dirac to symmetrize the Maxwell equations and to quantize the electric charge[32)]. These Dirac Monopoles have a magnetic charge g which is related to the electric charge e by

$$g/e = n/2\alpha \sim 68.5\,n \; ; \quad n = 1,2,\ldots \qquad (17)$$

The mass of these monopoles M_M is predicted to be (M_p = proton mass)

$$M_M \sim 2.56\, n^2 \cdot M_p \qquad (18)$$

Later, T'Hooft and Polyakov$^{34)}$ pointed out that monopoles appear as soliton solutions of the classical field equations and must exist in unified gauge theories. Their mass is much higher than that of Dirac monopoles, $M_M \sim M_G/\alpha$, where M_G is a typical mass of the gauge, e.g. 100 GeV for electroweak theories or 10^{14} GeV for unified theories. Clearly, this kind of monopole is inaccessible in e^+e^- interactions and our search is restricted to Dirac monopoles (18).

To search for monopoles in e^+e^- reactions, we make use of the high specific ionisation which is expected from (17)

$$dE/dx \sim (g/e)^2\, (dE/dx)_{min} \quad \text{for } \beta \sim 1 \qquad (19)$$

This is about 4700 times the ionisation of a minimum ionising particle for $n = 1$, and rises quadratically with n.

The experimental procedure to look for these highly ionising particles is quite simple and has been applied at PEP and PETRA. Plastic foils are wrapped around the vacuum pipe near an interaction point and later analyzed for traces of heavily ionising particles. Searches in the PEP16 experiment have yielded an upper limit for monopole production$^{30)}$

$$\sigma(e^+e^- \rightarrow \text{monopoles} + X) < 0.007 \cdot \sigma_{point}$$

for $M_M < 14$ GeV and n=1. For $n > 2$ these simple experiments are insensitive because the particles are absorbed in the beam pipe. Therefore, foils have been put into the vacuum of the beam pipe in the MARK J detector at PETRA. No results have been reported yet.

3. Search for New Scalars

Motivation to look for new scalar particles has recently come from two sources:

a) To explain symmetry breaking, models of increasing complexity have been proposed which require one or several (many) new scalar particles[35).

b) Supersymmetry associates a new scalar particle to each fermion[36,3d).

As already mentioned above, the search for scalars in e^+e^- is rendered more difficult compared to fermion searches by a factor 1/4 in the asymptotic cross section and a slowly rising threshold function $\sim \beta^3$ (see Fig. 1).

3.1 Search for Supersymmetric Particles

In supersymmetry, each fermion with spin J has one boson counterpart with spin J ± 1/2 and vice versa. Thus, to each particle, there exists a supersymmetric partner ("sparticle")[3d). Table 5 contains a few examples which will be relevant to the further discussion.

Table 5: Supersymmetric Partners

Particle	J	Sparticle	J ± 1/2
lepton l	1/2	slepton s_ℓ t_ℓ	0
photon γ	1	photino λ_γ	1/2
graviton	2	gravitino λ_g	3/2

Some properties of these hypothetical particles are illustrated in Fig. 15. The sleptons s_ℓ, t_ℓ (one for each helicity state of the lep-

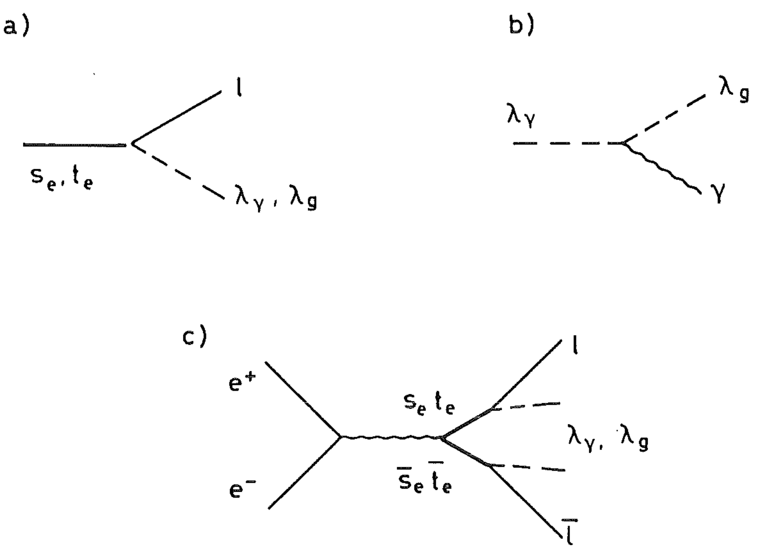


Fig. 15

Production and decay of supersymmetric particles

a) Supersymmetric lepton decay,

b) Model-dependent photino decay,

c) production and decay of supersymmetric leptons in e^+e^- annihilation

ton 1) decay rapidly into the related leptons and a photino λ_γ or gravitino λ_g (which could also be a goldstino if gravity were not included in the theory). The photino may be stable or may decay into a photon and a gravitino (Fig. 15b). This process is strongly model-dependent and will be discussed later.

3.1.1 Search for Direct Production of Supersymmetric Leptons

Pointlike sleptons are pair produced with the cross section (2) in e^+e^- annihilation and decay rapidly according to Fig. 15. Thus the signature is $(l = e, \mu, \tau)$

$$e^+e^- \rightarrow l^+l^- \quad \text{(acollinear)} \qquad (20)$$

Although this is a simple and clean signature in principle, background, in particular from radiative QED processes,has to be eliminated carefully. Many groups at PEP/PETRA have searched for sleptons. As examples, the results of the CELLO group on supersymmetric electron (t_ℓ, s_ℓ) and muon (t_μ, s_μ) searches and of the MARK J collaboration on a supersymmetric tau (t_τ, s_τ) search are shown in Figs. 16 and 17. It should be noted that the additional graph of λ_γ exchange contributes to the supersymmetric production and increases the expected rate considerably (Fig. 16a).

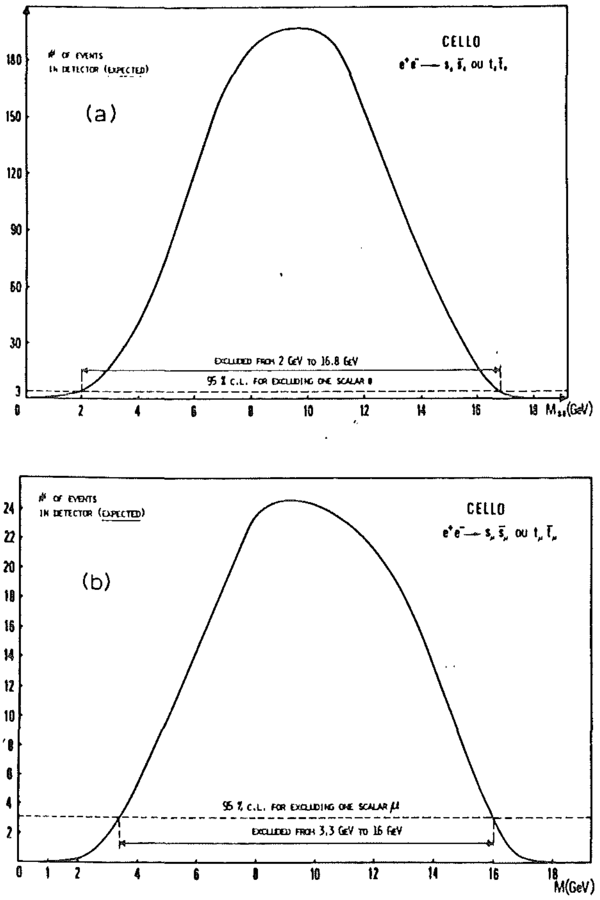


Fig. 16

Experimental limits on supersymmetric electrons and muons (CELLO)37)

(a) suypersymmetric electrons

(b) supersymmetric muons

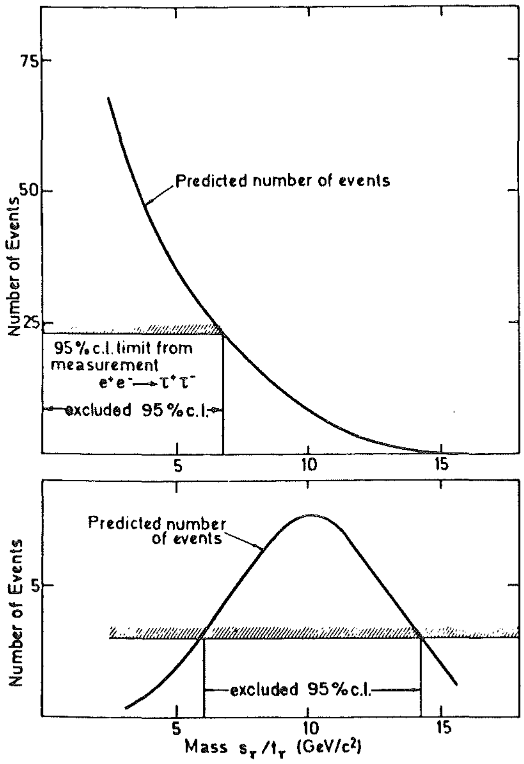


Fig. 17

Experimental limits on supersymmetric taus (MARK J)39)

This improves the experimental limits which can be obtained. The signature used by the MARK J group to search for supersymmetric taus is similar to (2c) in the case of the sequential lepton search and the hyperpion search discussed below. The results of the experimental searches at PEP/PETRA are summarized in Table 6. The value derived from the anomalous magnetic moment of the muon is also included.

Table 6: Experimental Lower Limits on the Masses of Supersymmetric Leptons in GeV (95% C.L.)

	$s_\ell t_\ell$	$s_\mu t_\mu$	$s_\tau t_\tau$ *	Ref.
CELLO	16.8	16	15.3	37
JADE	16		14	38
MARK J		15	14	14,39
MARK II			9.9	40
TASSO	16.6	16.4		41
MAC		13	13	13
g-2		13		42

* mostly from hyperpion search (c.f. Fig. 24)

The experiments quoted usually also give upper limits for the lower masses. These values have not been included in the table since the low mass region is already excluded by precision measurements on electron and muon pair production, in a way similar to that indicated in Fig. 17a for the case of τ's.

To improve the supersymmetric mass limit, a study of the single production shown in Fig. 18 was suggested[43)]. The electron would stay invisible in the beam pipe and a single supersymmetric electron would emerge under large angle and decay into an electron and a photino.

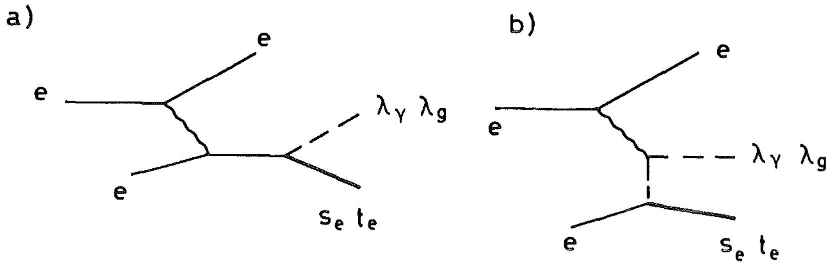


Fig. 18: Single production of a supersymmetric electron in e^+e^--collisions

Thus the experiment would have to look for single electrons at large angle. The authors claim that the supersymmetric electron mass limit could be pushed to about 1.25 times the beam energy.

3.1.2 Search for Virtual Supersymmetric Electrons and Search for Photinos

One may try to study the supersymmetric analogue to reaction (12) as given in Fig. 19a

$$e^+e^- \to \lambda_\gamma\bar{\lambda}_\gamma \qquad (21)$$

We have to distinguish the following two alternatives:

λ_γ, λ_g are stable

As λ_γ and λ_g are supposed to interact only very weakly, they will be invisible if they do not decay in the detector. Therefore, the only way to study this process experimentally would be through initial state radiation (Fig. 19b) as suggested by Fayet[44]. The expected rates of

$$\sigma(\lambda_\gamma\bar{\lambda}_\gamma\gamma) \sim 0.3 \text{ pb} \quad \text{for} \quad M_{s_e} = 20 \text{ GeV}$$

$$\sim 0.1 \text{ pb} \quad \text{for} \quad M_{s_e} = 40 \text{ GeV}$$

would lead to a signal of 10 ÷ 30 events for 100 pb^{-1}. In view of the

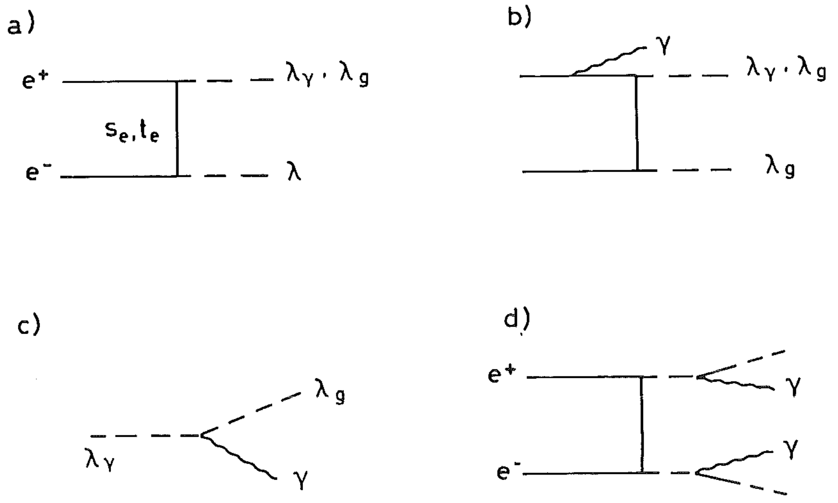


Fig. 19: Production and decay of photinos in e^+e^- annihilation

experimental problems of triggering on a single photon of 2 to 3 GeV and fighting the background from radiative QED processes, this is certainly a very low signal. It requires a very good trigger and complete solid angle coverage for electromagnetic showers.

λ_γ is unstable

If the photino is massive, with a mass larger than the gravitino mass, it will decay according to Fig. 19c with a lifetime[45)]

$$\tau_{\lambda_\gamma} = \frac{8\pi d^2}{M_{\lambda_\gamma}^{\;5}} \qquad (22)$$

where M_{λ_γ} is the photino mass and d is a parameter characterizing the symmetry breaking, which is unknown. If τ_{λ_γ} is such that λ_γ decays inside the detector, the process (21) would lead to two photons in the final state (Fig. 19d) with the experimental signature

$$e^+e^- \rightarrow \gamma\gamma + \text{missing energy} \qquad (23)$$

The CELLO group has searched for events of this type[46)]. Fig. 20

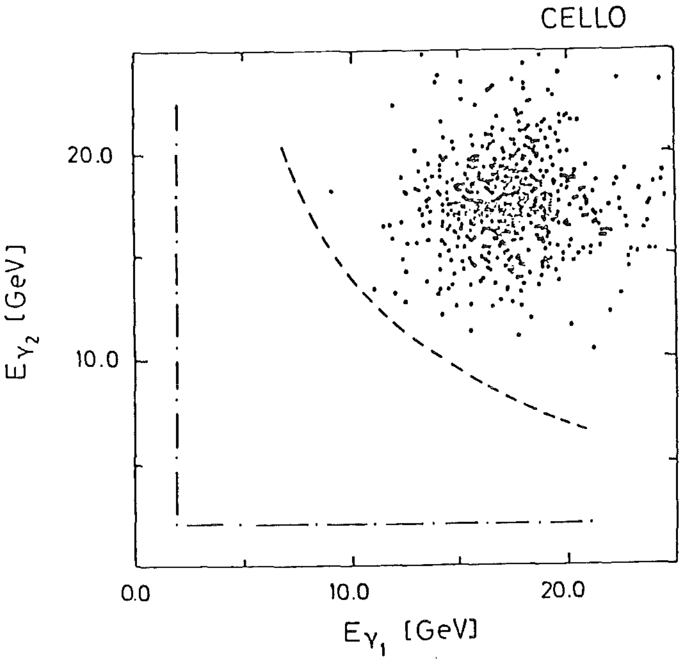


Fig. 20

Correlation of the two photon energies in the reaction $e^+e^- \rightarrow \gamma\gamma$ (CELLO) (Ref. 46)

shows the correlation of the energies of the two photons in reaction (23). All events pass the missing energy cut indicated in the figure. Fig. 21 shows the constraints which can be derived on the mass of the photino and the scale parameter d assuming m_{s_e} = 40 GeV, together with limits from cosmological arguments 56) and search for the decay $J/\psi \rightarrow$ nothing 42).

3.2 Search for Higgs Particles

3.2.1 Search for the Neutral Higgs Particle H^o

In the Standard Model with one Higgs doublet only, one physical particle, the neutral Higgs H^o, emerges after symmetry breaking.

Since H^o couples preferentially to large mass fermions, the best way to look for it in e^+e^- annihilation would be in the decay of heavy onium O 47) (Fig. 22a). The relative width is estimated to be (m_o,m_H = onium and Higgs mass)

$$\frac{\Gamma(O \rightarrow H^o\gamma)}{\Gamma(O \rightarrow e^+e^-)} \cong \frac{G_F\, m_o^2}{4\sqrt{2}\,\pi\,\alpha}\left(1 - \frac{m_H^2}{m_o^2}\right) \qquad (24)$$

which leads to the following branching ratios48)

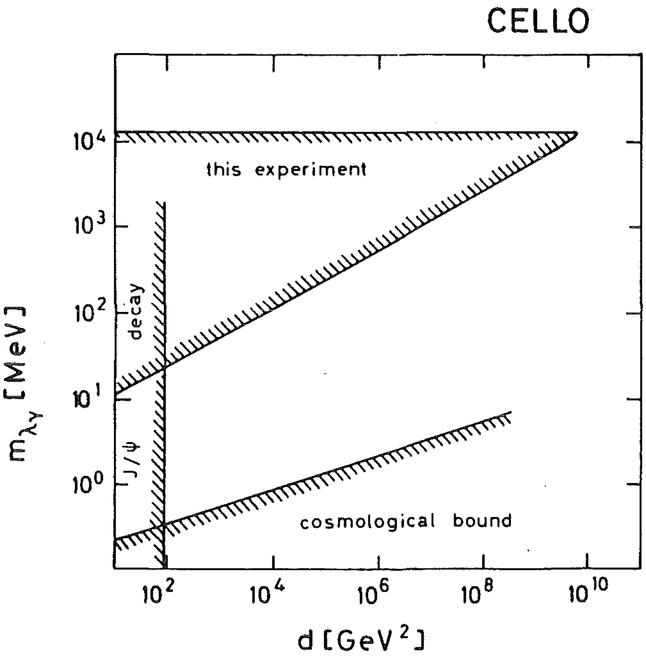


Fig. 21

Experimental bounds on the mass of the photino as a function of the scale parameter d of the supersymmetry breaking (CELLO)46)

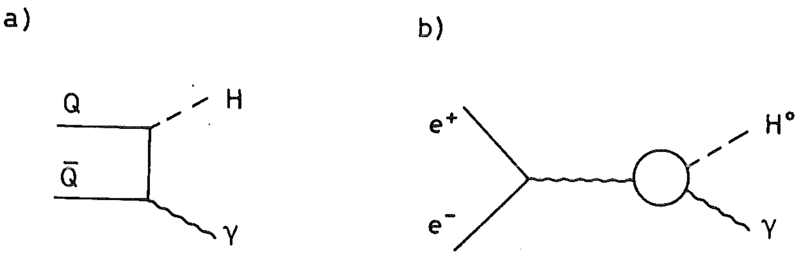


Fig. 22

Production of neutral Higgs particles in e^+e^- reactions

a) Decay of heavy onium

b) Production in the continuum

$$
\begin{array}{lcll}
BR(J/\psi \rightarrow H^o\gamma) & \simeq & 1/2 \cdot 10^{-4} & \\
BR(\Upsilon \rightarrow H^o\gamma) & \simeq & 2 \cdot 10^{-4} & \\
BR(t\bar{t}(^3S_1) \rightarrow H^o) & \simeq & 10^{-2} & (M_{t\bar{t}} = 40 \text{ GeV})
\end{array}
$$

An upper limit on the J/ψ branching ratio of 10^{-3} is quoted by the Crystal Ball group48).

Even if the mass of H^o were sufficently low, it would be very difficult to detect H^o on the J/ψ or Υ because of the low branching ratios. Toponium would certainly be an ideal place to look for H^o.

Another possible way of producing H^o in e^+e^- annihilation is shown in Fig. 22b. This production in the continuum is however highly suppressed since it involves heavy quark and vector boson loops. The cross section of[49)]

$$\sigma(e^+e^- \rightarrow H^o\gamma) \simeq 10^{-6} \sigma_{QED}$$

is hopelessly small. Fig. 23 shows the radiative background

$$e^+e^- \rightarrow \gamma + q\bar{q} \rightarrow \gamma + \text{hadrons} \qquad (25)$$

From the absence of any structure or deviation from the expectation for (25) an upper limit of $\sigma(e^+e^- \rightarrow H^o\gamma) \lesssim 10^{-2} \sigma_{QED}$ can be deduced (Ref. 3c,50).

3.2.2 Search for Charged Higgs Particles and Hyperpions

There are several reasons why the Higgs sector may be more complicated than proposed in the Standard Model e.g.[48)]

- CP violation may be due to Higgs fields
- asymptotically the electro-weak interaction is left-right symmetric
- Higgs particles have supersymmetric partners
- the strong CP problem is solved by Higgs particles.

In all these cases, charged Higgs particles $H^\pm$ will occur.

Moreover, in dynamical schemes of symmetry breaking like extended technicolour (ETC) many Goldstone bosons become physical particles and acquire mass (pseudo-Goldstone bosons, PGB). Some of these lie in the mass range accessible to high energy e^+e^- machines. In particular, in a minimal ETC, the colour singlet 0^- PGB's acquire their mass from electroweak interaction. The mass of the charged states, $P^\pm$ is then

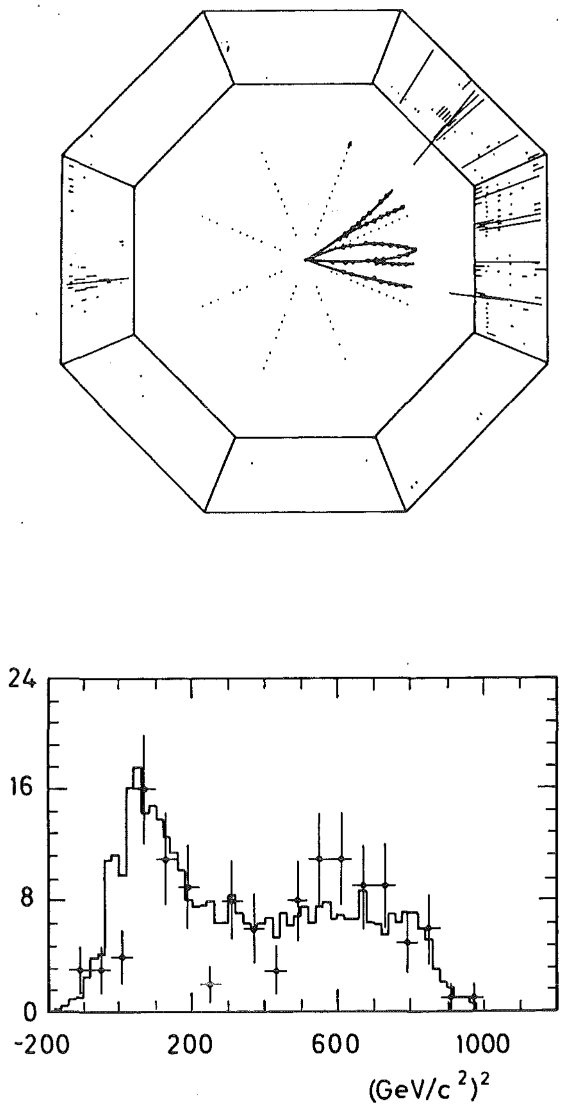


Fig. 23

Search for neutral Higgs in the reaction $e^+e^- \to \gamma$ + hadrons

a) hadronic event with an isolated photon as seen in the CELLO detector[50)]

b) Photon recoil mass spectrum (JADE) of events with an isolated photon[3c)]

predicted to be in the range[35)]

$$5\ \text{GeV} \lesssim M_{p^\pm} \lesssim 14\ \text{GeV} \tag{26}$$

Extensive searches for charged Higgs particles or hyperpions have been carried out at PEP and PETRA. Both types of particle have the same production and decay properties

$$\begin{array}{l} e^+e^- \rightarrow H^+H^- \\ \qquad \text{or } P^+P^- \text{ decay into heavy fermions} \\ \qquad\quad \begin{array}{l} \hookrightarrow \bar{c}s,\ \bar{c}b,\ \tau^-\nu \\ \hookrightarrow c\bar{s},\ c\bar{b},\ \tau^+\nu \end{array} \end{array} \qquad (27)$$

The relative branching ratios for hadronic and leptonic decays are given by

$$\frac{BR(H^+ \rightarrow c\bar{s})}{BR(H^+ \rightarrow \tau^+\nu)} = \frac{m_c^2}{m_\tau^2}\ \chi \qquad (28)$$

where χ is, a priori, an unknown parameter. In different models, χ may vary over a wide range (χ = 3 for Higgs, 1/3 or 27 for PGB's)[51]. We shall, therefore, consider χ as a free parameter and discuss the following cases (Fig. 24):

a) $\chi << 1$: $H^\pm \rightarrow \tau^\pm\nu$ Predominant

This situation is illustrated in Fig. 24a. Both H decay into τ and ν. The events look identical to the ones expected for supersymmetric τ's. If λ_γ is undetectable, $H^\pm$ decaying with 100% branching ratio into $\tau\nu$ is indistinguishable from s_τ or t_τ. Therefore, the limits derived for $H^\pm$ production can also be applied to s_τ (special case of $B_{\tau\nu}$ = 100% in Fig. 25, c.f. Table 6).

The CELLO[37] and MARK J [39] groups have used the decay $\tau \rightarrow$ 1 prong – signature (1) in Fig. 24a – to search for $H^\pm$ signals: an acoplanar pair of particles with missing energy. Signature (2) implies τ decays into all channels: 1 prong acoplanar with 3 or 5 prongs in the opposite hemisphere. The JADE collaboration used this signature in the combinations (1 prong – 3 prong) and (1 prong – 5 prong) whereas the MARK II group looked for the (1 prong – 3 prong) combination. The mass of the 3 or 5 prong system is restricted to less than the τ mass (< 2 GeV).

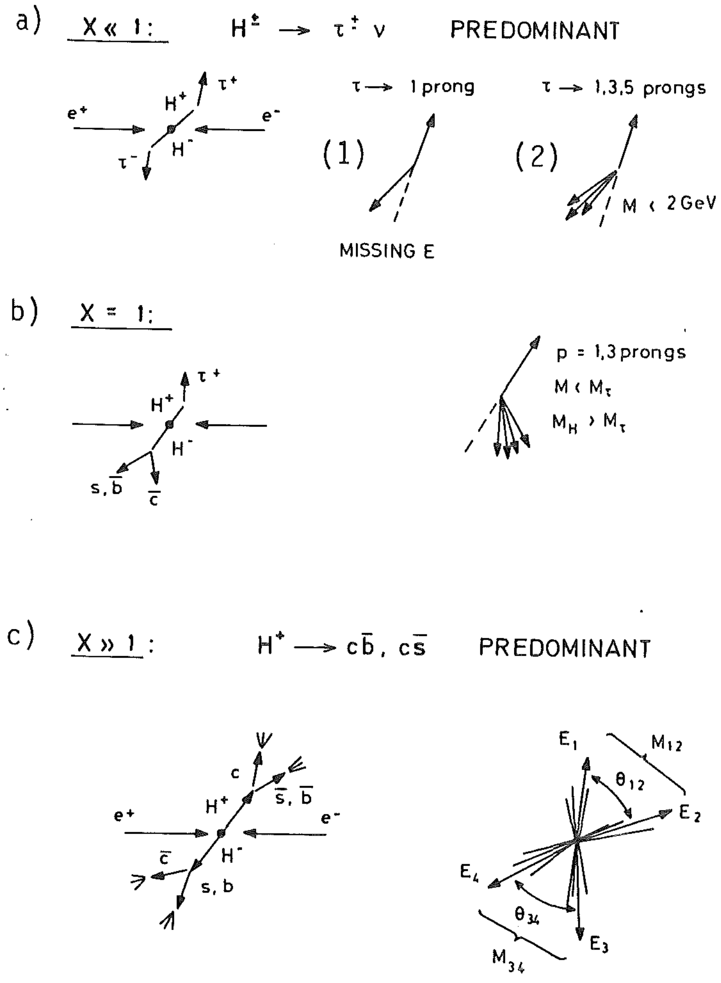


Fig. 24

Experimental search for charged Higgs particles and hyperpions

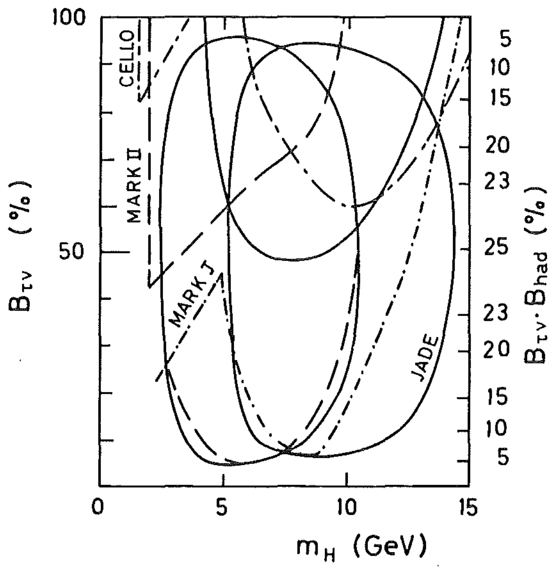


Fig. 25

Experimental bounds on the mass of the Higgs or hyperpions $H^{\pm}$ as a function of the leptonic and hadronic branching ratios. The areas included by the curves are excluded with 90% C.L.

b) $\chi \simeq 1$

In this case, both the leptonic and hadronic decay modes occur with similar branching ratios. The situation is described in Fig. 24b.

Four groups have looked for events characterized by one or three prongs (originating from the τ) acoplanar with a hadronic jet of mass $M_H > M_\tau$ (c.f. Fig. 24b)

group	M_H	$\tau \rightarrow P$	M_P	Ref.
JADE	> 2.5 GeV	1,3 prongs + γ's	< 2 GeV	38
MARK II	> 2 GeV	1 prong + γ's	< 2 GeV	40
MARK J	> 2 GeV	μ	-	39
MAC	> 2 GeV	μ	-	13

The results of searches a) and b) are summarized in Fig. 25 which shows the experimental boundaries for $H^\pm$ production as a function of mass and branching ratio. Combining the results of all groups, the mass range from about 3 to 13 GeV can be excluded except for very low leptonic branching ratios of about 10%. This interesting area is again shown in Fig. 26.

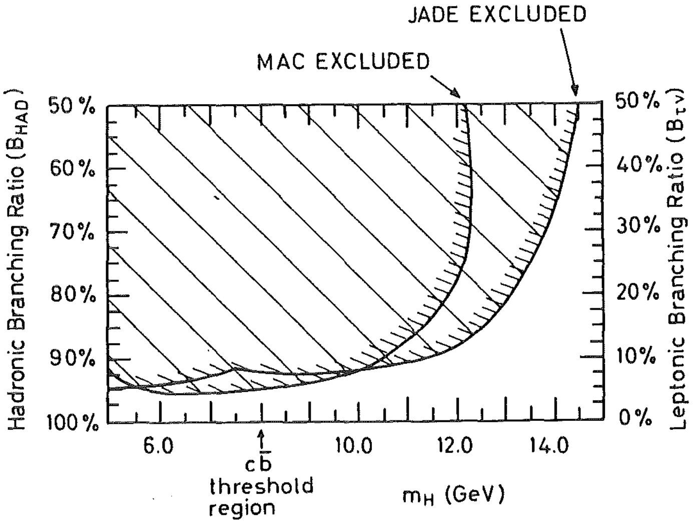


Fig. 26

Experimental bounds like in Fig. 25 (JADE, MAC)

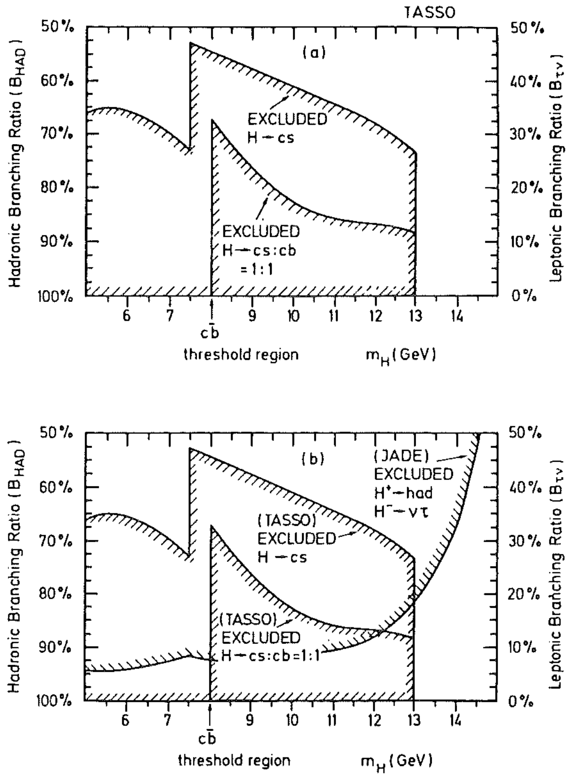


Fig. 27

Experimental bounds on the hyperpion mass (TASSO)52)

c) $\chi >> 1$, $H^{+} \to c\bar{b}$, $c\bar{s}$ predominant

To fill in the gap in Fig. 25, the TASSO collaboration has studied $H^{\pm}$ decays into hadrons according to Fig. 24c 52). 75 pb^{-1} with about 20 000 hadronic events at $\sqrt{s}$ = 34.5 GeV energy were analysed. The experimental procedure is illustrated in Fig. 24c. The group has searched for four jet events and determined the jet energies, E_i, and the opening angles, θ_{ij}, between jets. Cuts are then applied according to the constraint that two pairs of jets have to form systems of equal invariant mass with beam energy. Two events survive in the 5 to 7.5 GeV mass range, no candidates are found between 7.5 and 13 GeV. The resulting limit on the leptonic branching ratio as a function of $H^{\pm}$ mass is shown in Fig. 27. Together with the limits from Fig. 26, this excludes charged Higgs particles or technicolour particles in the mass range 5 to 13 GeV. Similar results are quoted by the MAC group13).

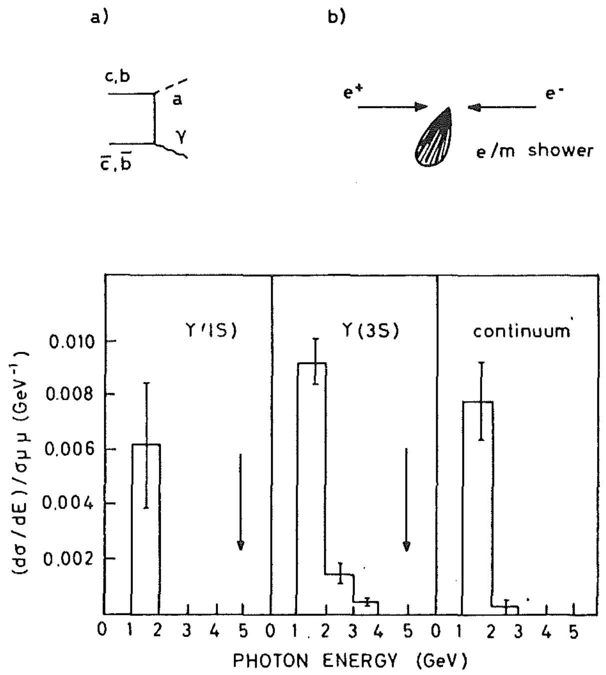


Fig. 28

Search for the axion at the Υ resonances. Events with one single photon of beam energy (E_γ > 5 GeV). Arrows indicate, where an axion signal would be expected (CUSB)[55]

3.2.3 Search for the Axion

To explain the absence of P and T violation in QCD, it has been proposed to introduce two Higgs doublets ϕ_1 and ϕ_2. In such a model, a light neutral pseudoscalar particle appears, the axion a [53]. Similar to H^o, heavy quarkonia decay into an axion and a photon (Fig. 28a). The branching ratio for the decay of J/ψ and Υ can be precisely predicted up to a parameter $X = \langle\phi_2\rangle / \langle\phi_1\rangle$ which is the ratio of the expectation values of the two Higgs fields. Since c and b have opposite weak isospin, the two branching ratios have different proportionality to X

$$\begin{aligned} BR(J/\psi &\rightarrow \gamma a) \sim X^2 \\ BR(\Upsilon &\rightarrow \gamma a) \sim 1/X^2 \end{aligned} \qquad (29)$$

so that the product of the two is a precisely predictible number

$$\mathrm{BR}(J/\psi \rightarrow \gamma a) \times \mathrm{BR}(\Upsilon \rightarrow \gamma a) = B^{\Upsilon}_{\mu\mu} \cdot B^{J/\psi}_{\mu\mu} \frac{G_F^2 m_c^2 m_b^2}{2\pi^2\alpha^2}$$

$$= (1.6 \pm 0.3) \times 10^{-8} . \qquad (30)$$

The experimental signature for reaction (29) is rather clear (Fig. 28b)

$$e^+e^- \rightarrow J/\psi \text{ or } \Upsilon \rightarrow \gamma + \text{NOTHING} \qquad (31)$$

if the axion decays outside the detector ($M_a << 10$ MeV).

The Crystal Ball group has published a negative result for a search at the J/ψ resonance[54)]

$$\mathrm{BR}(J/\psi \rightarrow \gamma a) < 1.4 \cdot 10^{-5} . \qquad (32)$$

Recently, the CUSB and CLEO groups have looked for a signal at the Υ(1s) and Υ(3s) resonances. Fig. 28 shows the CUSB result. No events have been found (arrows in Fig. 28) which implies the following limits[55)]

$$\begin{array}{llll} \text{CUSB:} & \mathrm{BR}(\Upsilon(1s) \rightarrow \gamma a) & < 3.5 \cdot 10^{-4} & (90\%\ \text{C.L.}) \\ \text{CUSB:} & \mathrm{BR}(\Upsilon(3s) \rightarrow \gamma a) & < 1.2 \cdot 10^{-4} & (90\%\ \text{C.L.}) \\ \text{CLEO:} & \mathrm{BR}(\Upsilon(1s) \rightarrow \gamma a) & < 9.0 \cdot 10^{-4} & (90\%\ \text{C.L.}) \end{array} \qquad (33)$$

The combined result of (32) and (33) is then

$$\mathrm{BR}(\Upsilon \rightarrow \gamma a) \times \mathrm{BR}(J/\psi \rightarrow \gamma a) < 0.6 \times 10^{-9} \quad (90\%\ \text{C.L.})$$

which is more than an order of magnitude lower than the expectation (30). Thus the "standard" axion is ruled out.

4. Summary

We can summarize the search for new particles as follows

Fermions

- There is now (indirect) experimental evidence that the "old" sequential heavy lepton τ has its own neutrino.
- No new leptons (sequential, stable, neutral, excited) have shown up in the PEP/PETRA energy range.
- The mass limit on toponium is larger than 36.75 GeV.
- No free quarks or monopoles have been seen at PEP/PETRA.

Scalars

- If they exist, supersymmetric leptons have masses larger than about 16 GeV.
- Charged Higgs particles are excluded in the mass range from 5 GeV to 13 GeV.
- Charged technipions do not exist in the proposed mass range from 5 GeV to 13 GeV.
- The "standard" axion does not exist.

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