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SEARCH FOR NEW PARTICLES AT PETRA

by

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Intensive searches for new particles have been performed in e^+e^- annihilation at PETRA at energies up to 36.7 GeV. No new quark and no new lepton have been found. Also the existence of spin zero partners of leptons predicted by supersymmetric theories is excluded up to masses of about 16 GeV. Furthermore, no charged Higgs particles or technipions have been observed.

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I. INTRODUCTION

The search for new particles is most exciting when new particles are discovered. Unfortunately many searches do not have this success. Nevertheless they need to be done, in order to restrict the theoretical choices for new models. From an experimental point of view the motivation is obvious: because PETRA runs at the highest energy reached in e^+e^- collisions, it provides an ideal opportunity to look for new particles.

Five experiments, CELLO, JADE, MARK-J, PLUTO and TASSO took data at PETRA. I will briefly summarize their results on new particle searches[1,2], without going into the details of detectors and selection criteria. For this the reader should consult the publications of the different groups as referenced in the text. My talk will be divided into three parts, search for new quarks, new leptons and new fundamental scalar particles.

2. SEARCH FOR NEW QUARKS

2.1 NEW SIXTH QUARK (TOP-QUARK)

The symmetry between leptons and quarks and the existence of the b-quark leads us to predict the existence of the top quark in order to fill the third quark doublet. From the width of the Τ resonance we conclude that the b-quark has the charge 1/3 in units of the elementary charge e and we infer that the top quark should have a charge 2/3. In general we also search for a new quark with charge 1/3, but the sensitivity of the experiments is a factor four smaller due to the reduced production cross-section.

Four methods to search for these quarks have been employed by the PETRA experiments. The simplest method uses the measurement of the ratio of the hadronic to the pointlike QED cross-section:

$$R = \frac{\sigma(ee \to \text{hadrons})}{\sigma_{pt}} \tag{1}$$

where $\sigma_{pt} = \frac{4\pi\alpha^2}{3s}$ and s is the c.m. energy squared. The ratio R depends on the number and charges of the produced quark flavors:

$$R = 3\sum_i Q_i^2\,(1+\delta_{QCD} + \delta_{weak}) \tag{2}$$

$\delta_{QCD} \simeq \frac{\alpha_s}{\pi}$ is a QCD-radiative correction and δ_{weak} is a correction due to weak interaction effects. Both corrections are small. For $\alpha_s \simeq 0.17$ we obtain

δ_{QCD} = +5.4% and for $\sin^2\theta_w$ = 0.23 the weak correction amounts to +1.2%. The QED radiative corrections[3] are rather large and are between -25% and -35% for energies between 12 and 35 GeV. Since the QED radiative corrections depend on the experimental cuts, only radiatively corrected data are presented. For five quark flavors u, d, s, c, b we expect a value R = 3.91. The production of a new quark with charge 2/3 or 1/3 should increase the value by ΔR = 1.41 or 0.36 respectively.

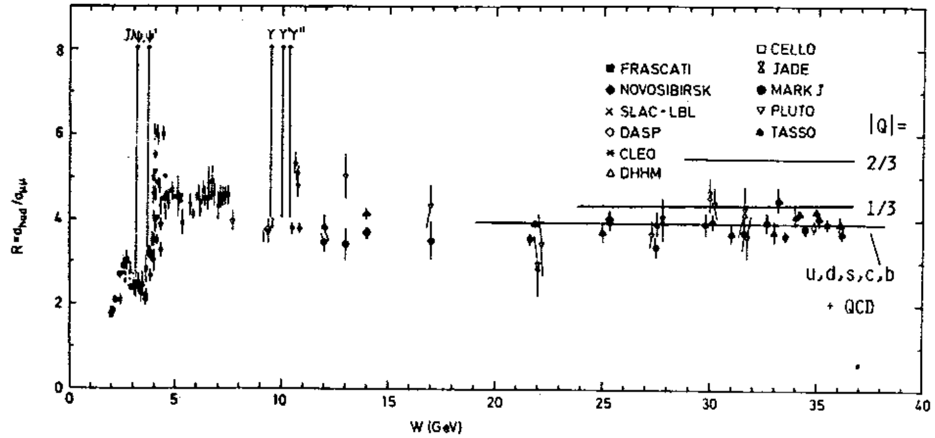


Fig. 1: Results on the relative hadronic cross-section at PETRA (Ref. 4-9) compared with the lower energy measurements (Ref. 10). The prediction of QCD for five quarks and the increase expected for a sixth quark with charge 1/3 and 2/3.

Figure 1 summarizes the measurements[4-10] at high energies. Although the statistical errors are very small, the systematic errors are estimated by the PETRA groups to be between 5% and 10%. Therefore the production of a new quark of charge Q = 2/3 can be excluded, while the increase of R by a new quark of charge 1/3 lies within the systematic error and cannot be excluded by this measurement alone.

A measurement of R can also be used to search for bound states of new quarks, such as the toponium. As the resonances are about 1 to 2 GeV below the continuum threshold, a search for these could reveal the existence of a new quark flavor in cases where the energy is not sufficient to produce unbound $q\bar{q}$ pairs of the new flavor. A scan has been performed at PETRA by varying the c.m. energy in steps of 20 MeV, which is about 75 per cent of the energy resolution of PETRA. Unfortunately the observed height of the resonance is strongly decreased as a result of the smearing caused by the energy resolution of the machine, which is much larger than the width of the resonance. The height of the resonance depends on the partial

resonance width Γ_{ee} and the branching ratio B_h of the resonance into hadrons. Four experiments[4,5,6,8] have taken data when the scan was performed between 33 GeV and 36.72 GeV and they obtained the upper limits[1] listed in Table I.

Experiment	$\Gamma_{ee} \cdot B_h$ (90% C.L.)
CELLO	< 1.8 keV
JADE	< 1.2 keV
MARK-J	< 1.0 keV
TASSO	< 1.3 keV
combined	< 0.6 keV

Table I: Upper limit of the product $\Gamma_{ee} \cdot B_h$ with 90% confidence.

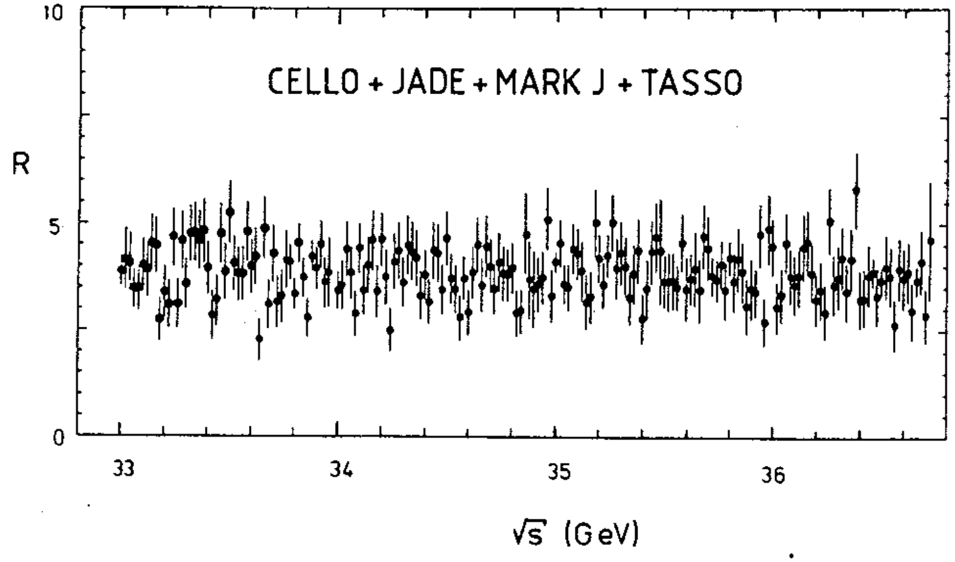


Fig. 2 : Relative hadronic cross-section combined from measurements of CELLO, JADE, MARK-J, and TASSO in the highest energy region, where the scan was performed (from Ref. 1).

From the combined measurements[1] in Figure 2 an upper limit of 0.6 keV can be given with 90% confidence. Assuming a pessimistic value of B_h = 70% one finds that Γ_{ee} is smaller than 0.86 keV. From the J/ψ and ϒ resonances we expect $\Gamma_{ee}/Q^2 \simeq 12$ keV, which gives 5.3 keV (1.3 keV) for Q = 2/3 (1/3). Therefore the production of a resonance with a quark of charge 2/3 can safely be excluded, while the value for a charge 1/3 quark is at the limit.

A higher sensitivity for the production of quarks with Q = 1/3 can be obtained from an analysis of the event shape, because quarks slightly above threshold have a very low velocity and should fragment into a very broad jet. In order to select those events, CELLO and TASSO used the aplanarity $A = 3/2\, Q_1$, where Q_1 is the smallest eigenvector of the sphericity tensor. The MARK-J group studies the thrust distribution, which is compared in Figure 3a with the QCD prediction for $\alpha_s = 0.17$ and in Figure 3b with the prediction including the production of a new quark with a mass of 15 GeV and a charge 1/3 or 2/3. Applying the cuts $A > 0.15$ or $T < 0.8$ the different groups obtain the numerical values given in Table II.

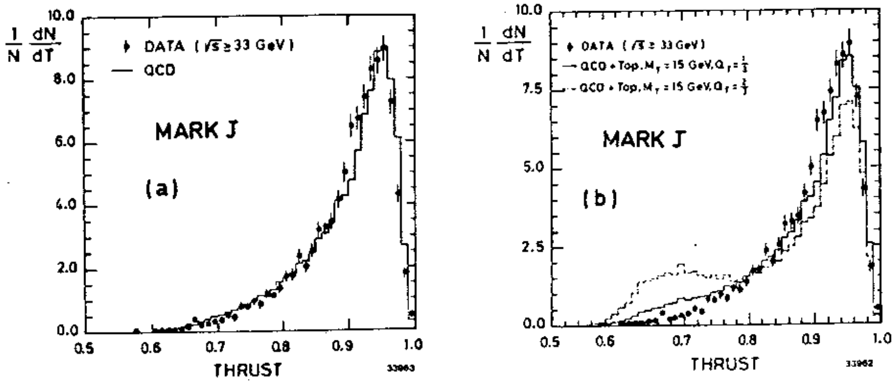


Fig. 3: Thrust distribution measured by MARK-J is compared with the QCD prediction (Fig. 3a) and with QCD prediction including the existence of a "top" quark with a mass of 15 GeV and a charge of 1/3 or 2/3 (Fig. 3b).

	CELLO[4]	TASSO[1]	MARK-J	
	A > 0.15		thrust < 0.8	
Data	9	12	479	
QCD(u,d,s,c,b)	5.2±1.4	11±1	513	
quark mass	16 GeV	15 GeV	15 GeV	8 GeV
QCD +(Q = 2/3)	96 ± 4	138	1416	991
QCD +(Q = 1/3)	31 ± 1	43	774	667

Table II: Number of events found selecting a broad event-shape and the comparison with the QCD predictions.

From these studies it follows that the production of a new quark with a charge of Q = 2/3 and 1/3 is excluded up to quark masses of 16 GeV.

The fourth method of searching new quarks is the analysis of hadronic events which contain a muon track (μ-inclusive events). The muon candidates originate from the decays of mesons or are misidentified hadrons which penetrate the muon absorber. Mesons containing a heavy quark such as charm, bottom or top are very short-lived and produce "prompt" muons originating from the intersection region. In the quark spectator model we describe the meson decays as the decays of a quark. We expect that the top quark preferentially decays into a bottom quark, which again decays into a charm quark. As all the quarks have a similar branching ratio for a semi-muonic decay, we should observe a large increase of μ-inclusive events above the threshold for top production[11-13]. Reversing the argument, the selection of μ-inclusive events should enhance the signal for a new quark in the thrust distribution[12]. In Figure 4a the thrust distribution of μ-inclusive events from MARK-J is compared to the one for all hadronic events. Both distributions agree very well, while the predictions including a new quark of charge 1/3 or 2/3 disagree with the measurement (Figure 4b). To state the results quantitatively we denote the μ-inclusive cross section, normalized to the pointlike cross section by R_μ and set a limit on ΔR_μ, the contribution of a new quark to this ratio. Selecting events with a transverse momentum to the hadron jet axis of $P_T(\mu) > 2$ GeV and a

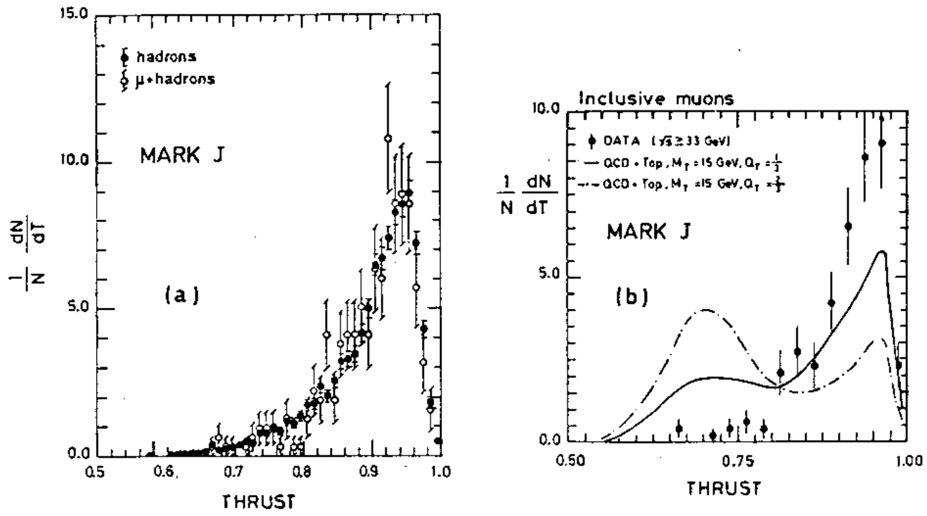


Fig. 4: The thrust distribution of μ-inclusive events from MARK-J is compared with the one for all hadronic events (Fig. 4a) and with the QCD prediction including a top quark of a mass of 15 GeV and a charge of 1/3 or 2/3.

sphericity S > 0.5 the JADE group[11] obtains a 90% confidence limit of $\Delta R_\mu < 0.005$ for a quark mass of 16 GeV. The MARK-J group[12] selects μ-inclusive events with thrust T < 0.75 and sets a 95% confidence limit of $\Delta R_\mu < 0.008$ (0.02) for a quark mass of 14 GeV (8 GeV). If the charge of the new quark is Q = 1/3, we expect a ΔR_μ of about 0.03 to 0.04. Therefore, the study of μ-inclusive events sets a strong and independent limit on the production of new quark with either charge.

2.2 SEARCH FOR FREE QUARKS

The JADE detector[14] makes simultaneous measurements of the momentum p and the energy loss dE/dX of a particle. Because the momentum is determined from the curvature in a magnetic field, one really measures an apparent momentum P/Q, where Q is the charge of the particles in units of e. The energy loss is proportional to Q^2 and depends on the speed of the particle. For a fixed value of P/Q the ionisation depends only on the charge and the mass of a particle. For a certain mass interval we can therefore search for free quarks of charges 1/3 and 2/3. The JADE group[15] has studied two production mechanisms, the pair production $e^+e^- \to q\bar{q}$ and the inclusive production $e^+e^- \to q\bar{q}X$. No candidate was found for a quark of charge 1/3 or 2/3 and this sets a limit on the production cross-section for different quark masses (Fig. 5). In order to extrapolate the measurements of the inclusive reaction to regions where the separation of quarks from hadrons would not have been possible, it is necessary to make an assumption for the form of the momentum distribution. Two extremes were chosen, an exponential distribution (curve I), as measured for pions, and a flat momentum distribution.

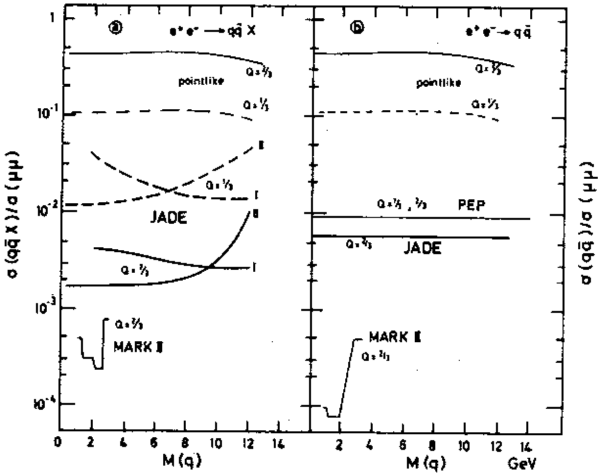


Fig. 5:

Upper limits with 90% confidence for the production cross-section for free quarks obtained by the JADE experiment[15]. The momentum distribution of the inclusive quark production has been assumed to be exponentially falling (curve I) or flat (curve II).

3. SEARCH FOR NEW LEPTONS

3.1. NEW SEQUENTIAL CHARGED LEPTONS

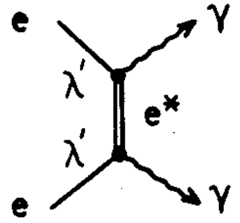
The energy thresholds for the τ-lepton and charm production in e^+e^- annihilation nearly coincide. If another charged heavy lepton exists it could well be produced below the top threshold thus repeating the situation at the charm threshold. Because we believe that quarks and leptons are related to each other, we would consider a new lepton as a first indication of a new family of quarks. The search for this new lepton proceeds in analogy to the tau lepton. The decays are expected to go into a lepton and neutrinos or into hadrons with a relatively low multiplicity and a neutrino. A typical signature is a muon in one hemisphere of the detector and hadrons in the other hemisphere. There are two ways to search for a new charged heavy lepton. If its mass is near the beam energy, we would expect events where the muon is acollinear with the hadron jet. If the mass is small, i.e. of the order of the tau mass, the events are very similar to tau pair production. Because the measured τ cross section agrees well with the QED prediction, we can exclude the production of a new lepton with a low mass, if we assume that QED correctly predicts the tau cross section. Four PETRA experiments have been searching for a new charged lepton and Table III presents their results[1,16]. Summarizing, we can say that the existence of a new heavy charged lepton is excluded with 95% confidence for masses less than 18.1 GeV.

Experiment	Lower Limit for the Mass with 95% C.L.
JADE	18.1 GeV
MARK-J	16 GeV
PLUTO	14.5 GeV
TASSO	15.5 GeV

Table III: Lower limits on the mass of a heavy charged lepton (Ref. 1 and 16).

3.2. EXCITED LEPTONS

If leptons are composite particles[17], it should be possible to observe excited states. The existence of an electron e* having the same quantum numbers as the electron, would modify the angular distribution of the reaction $e^+e^- \to \gamma\gamma$ due to the exchange of an excited



electron[18]. This process can be described by the following interaction Lagrangian

$$L = \frac{\lambda' e}{2M_{e^*}} \bar{\psi}_{e^*} \sigma_{\mu\nu} \psi_e F^{\mu\nu} + h.c. \qquad (3)$$

where M_{e^*} is the mass of the heavy electron and λ' is the coupling at the $ee^*\gamma$ vertex. The PETRA experiments[19,20] find no deviation of the measured $\gamma\gamma$ cross section from the QED prediction and give a limit on the mass M_{e^*} and/or on the coupling λ'.

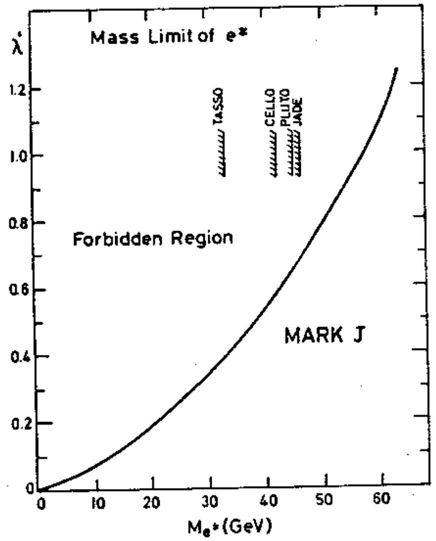


Fig. 6:

Upper limit (95 % C.L.) on the coupling λ' of a heavy electron as a function of its mass as determined by the MARK-J experiment[19]. Also indicated are the mass limits for λ' = 1 obtained by other PETRA experiments[20].

Figure 6 shows their results[19,20]. The MARK-J group determines a lower limit for the coupling of a heavy electron as a function of its mass. The other PETRA experiments give a mass limit for λ' = 1. With this assumption the mass of the heavy electron should be larger than 58 GeV.

A spin 1/2 excited state of the muon could be produced by the reactions $e^+e^- \to \mu^*\mu$ or $e^+e^- \to \mu^*\mu^*$. The coupling λ for the $\mu^*\mu$ production is defined by the following interaction Lagrangian

$$L = \lambda e \bar{\psi}_{\mu^*} \sigma_{\beta\delta} \psi_\mu F^{\beta\delta} + h.c. \qquad (4)$$

If the μ^* is massive and decays rapidly into a muon and a photon, the $\mu^*\mu$ events would be contained in an event sample of radiatively produced muon pairs[3] $e^+e^- \to \mu^+\mu^-\gamma$. If events with an excited muon are present, the invariant mass distribution should show a peak. The mass distribution agrees well with the QED prediction for radiative muon-pair production, as shown in Figure 7.

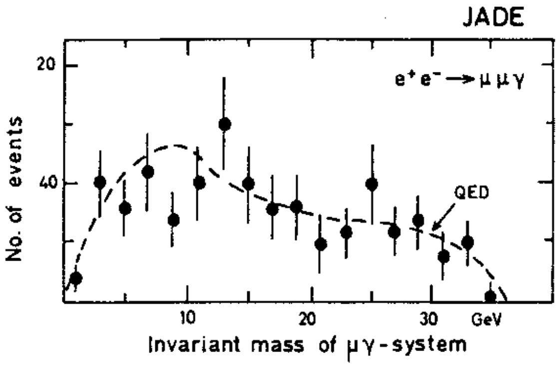


Fig. 7:

Invariant mass distribution of the (μ, γ)-system compared with the QED prediction for radiative events of the reaction ee → μμ(γ). The data are from the JADE experiment (from Ref. 1).

We compute the maximum number of events that can be attributed to an excited muon in every mass interval, and determine an upper limit for the coupling λ as a function of mass.

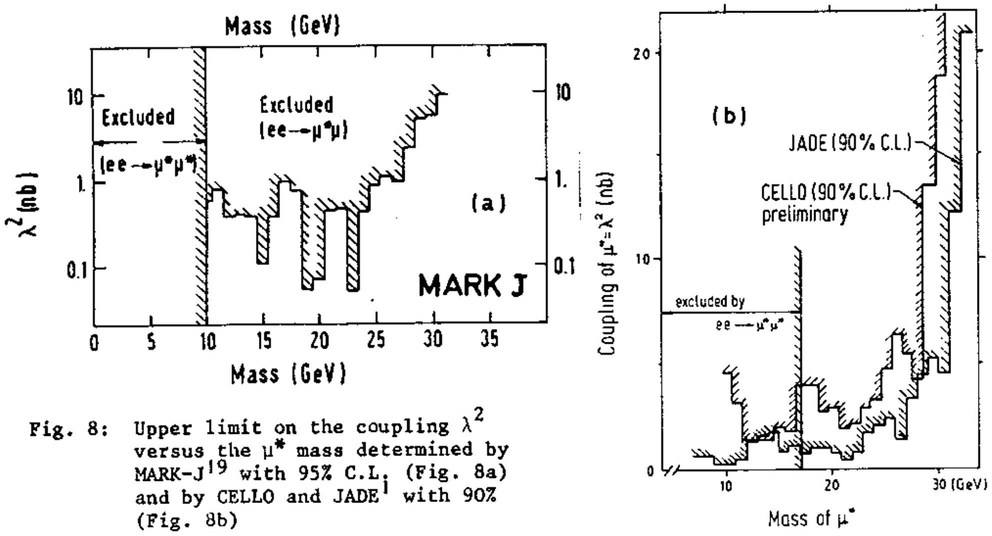


Fig. 8: Upper limit on the coupling λ^2 versus the μ^* mass determined by MARK-J[19] with 95% C.L. (Fig. 8a) and by CELLO and JADE[1] with 90% (Fig. 8b)

The results of the different PETRA groups[1,19] are shown in Figure 8. If the mass is less than half the c.m. energy, the excited muon can be pairproduced with a cross-section:

$$\sigma = \frac{1}{2}(3\beta-\beta^3) \cdot \frac{4\pi\alpha}{3s} \qquad (5)$$

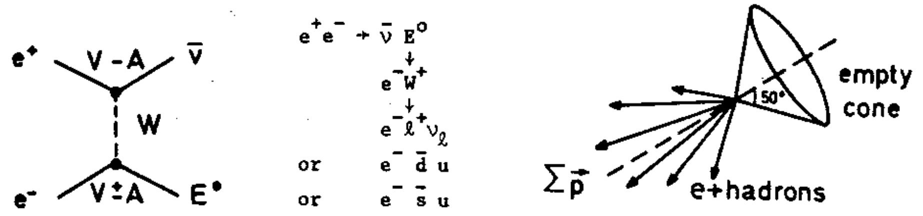
If the μ^* mass is less than 17 GeV, this cross-section is larger than 30% of the μ-pair cross-section at $\sqrt{s}$ = 35 GeV. Because such a signal is clearly absent in the data, the existence of a low mass excited muon is also excluded.

3.3. STABLE CHARGED LEPTON

It has been suggested[21] that if a fourth family of leptons exist, the corresponding neutrino could be more massive than the charged lepton thus leaving this new lepton relatively stable. It will be pair produced by the reaction $e^+e^- \to L^+L^-$ with a cross-section given in (4). The events would be very similar to those of the reaction $e^+e^- \to \mu^+\mu^-$ with the exception that the lepton momentum would be lower due to its high mass. The MARK-J group[19] has been searching for an excess of events in the μ-pair sample and excludes the existence of a stable lepton with a mass smaller than 14 GeV with 95% confidence.

3.4. HEAVY NEUTRAL ELECTRON

There have been many attempts to modify the standard elecroweak theory SU(2) x U(1). One such possibility is to introduce a heavy neutral lepton. If the neutral current is diagonal, the neutral lepton cannot be produced by neutrino interactions, but it can be produced in e^+e^- reactions[22] by the exchange of a W, where its coupling could be V ± A.



(a) (b) (c)

Fig. 9: Production (a), decay (b), and event signature (c) of the heavy neutral electron.

The JADE group[1] searched for events where the heavy neutral electron E^0 would decay into an electron and hadrons (Fig. 9). Because the recoiling neutrino does not interact, there should be no particle in the region opposite to the hadron and electron tracks. To be precise, they required a cone of half opening of 50° to be free of particles (Fig. 9c). The JADE group finds no events of this type and, with 95% confidence, excludes the existence of a heavy neutral electron with a mass between 3 and 17 GeV or between 3 and 20 GeV for a (V-A) or a (V+A) coupling, respectively.

4. SEARCH FOR FUNDAMENTAL SCALAR PARTICLES

4.1. SCALAR LEPTONS OF SUPERSYMMETRY

Supersymmetry[23] is a promising framework for the introduction of gravity into a scheme for unification of all interactions. Supersymmetry relates particles with different spin and in contrast to conventional unification schemes which relate quarks and leptons with the same spin, supersymmetry postulates that ordinary particles have partners, whose spins are 1/2 unit smaller or larger. In the simplest version, spin-1/2 leptons and quarks have spin-0 partners. For every lepton there are two partners s_ℓ and t_ℓ which are associated with the left-handed and right-handed parts of the lepton field. Because s_ℓ and t_ℓ are charged, and if they are point-like, they can be pair produced in e^+e^- annihilation with a cross-section

$$\sigma_{s\bar{s}} = \frac{1}{4}\beta^3\,\sigma_{pt} \qquad (4)$$

where $\beta = v/c$ and $\sigma_{pt} = 4\pi\alpha^2/3s$. The particles s_ℓ and t_ℓ would then decay rapidly into the corresponding lepton ℓ and a photino or goldstino. Since the photino and goldstino are expected to interact very weakly with matter, we would observe only a lepton-antilepton pair in the final state.

$$\begin{tikzcd} e^+e^- \to & s_\ell \arrow[dd] & \bar{s}_\ell \arrow[d] \\ & & \ell^+ + \text{antiphotino (antigoldstino)} \\ & \ell^- + \text{photino (goldstino)} & \end{tikzcd} \qquad (5)$$

A search has been made at PETRA for the spin-0 partner of leptons[24,25]. If the scalar leptons have high masses, the events of reaction (5) can be selected by demanding two acoplanar leptons, whose energy does not add up to the full c.m. energy, because the photino or goldstino is unobserved. The acoplanarity angle is defined as the angle between the planes formed by the beam axis and each of the two particle momenta. It is relatively insensitive to the effects of initial state bremsstrahlung and therefore preferred over the acollinearity angle between two particles. Additional cuts are necessary to reduce the background from the two photon reaction and higher order QED reactions. The CELLO group has also been searching for the supersymmetric partner of the tau lepton[25], selecting taus from their decays into a charged particle and neutrinos, using similar cuts to those described above. CELLO, JADE, MARK-J and PLUTO have been searching for scalar leptons, but no signal has been detected. If the masses of the scalar leptons are much lower than the beam energy, the events tend to be collinear and therefore are very similar to the pair production of normal leptons. In that case we would find an excess in the corresponding cross section for $e^+e^- \to \ell^+\ell^-$. Because the measurements agree well with the QED prediction, the existence of a supersymmetric partner of leptons can also be excluded in this mass range. Figure 10 shows the result of the CELLO group for a scalar muon and electron. Clearly, a large range of masses is excluded. The results of all PETRA groups are listed in Table IV. They show that the existence of supersymmetric partners of leptons is excluded for masses below 16 GeV for a scalar electron or muon and below 15 GeV for a scalar tau.

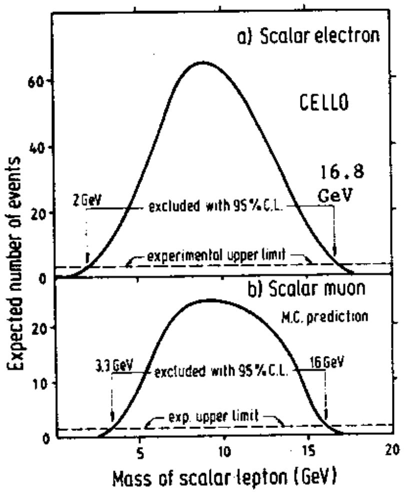


Fig. 10: Predicted number of events compared to experimental upper limit for a scalar electron and muon as a function of its mass. The result is from the CELLO group[25].

Experiment	Mass Range Excluded with 95% C.L. for a Scalar electron	muon	tau
CELLO	(2 - 16.8) GeV	(3.3 - 16) GeV	(6 - 15.3) GeV
JADE	< 16 GeV	-	(4 - 13) GeV
MARK-J	-	(3 - 15) GeV	m_τ - 14 GeV
PLUTO	< 13 GeV	-	-

Table IV: Mass range of scalar leptons excluded with 95% C.L. be PETRA experiments[24,25].

4.2. CHARGED HIGGS PARTICLES OR TECHNIPIONS

Charged Higgs particles[26] become necessary when symmetry breaking in SU(2) x U(1) models is non-minimal or when the group structure of the electroweak interaction is extended. Other theories called technicolor or hypercolor theories[27] give the spontaneous symmetry breaking a dynamical origin and use composite Higgs fields. In order to make the fundamental fermions massive, the technicolor model has to be extended thus generating a large number of Goldstone bosons. Some of the pseudo Goldstone bosons could be charged and light and they are called technipions, in analogy to the pions in QCD. Both charged Higgs particles $H^\pm$ or technipions $\pi'^\pm$ should couple preferentially to the heaviest fermions, such as τ lepton or c quarks. Their production and decay leads to the following reactions[28]:

$$\begin{array}{l} e^+e^- \to H^+ + H^- \\ \qquad\qquad\qquad \llcorner\!\!\longrightarrow \tau\nu \to \left\{\begin{array}{l}\mu\nu\nu\\ \text{or}\\ \text{hadrons} + \nu\end{array}\right. \\ \qquad\qquad \llcorner\!\!\longrightarrow c\bar{s} \to \text{hadrons} \end{array} \tag{6}$$

The events are characterized by having either two acollinear hadron jets or a muon acollinear to one hadron jet. In order to suppress background from two photon reactions and inclusive muon production the cuts are rather complicated[1,25]. The JADE group[1] has studied the reaction where one of the technipions or Higgs particles decays into a tau and a neutrino with a branching ratio B_τ and the other particle decays into hadrons with a branching ratio $(1-B_\tau)$. The CELLO group[25] has been searching for events where both technipions decay into a tau and a neutrino. In both searches the branching ratio B_τ and the mass $m_{\pi'}$ of the charged Higgs particle or technipion has been varied. The results are shown in Figure 11, which displays the regions in the $(m_{\pi'}, B_\tau)$ plane, where the existence of a Higgs particle or technipion is excluded with 90% confidence. Note that the mass limits for B_τ = 100% are identical to those for a scalar tau-lepton, since it has the same event signature. Because the measured τ pair cross section agrees well with the QED prediction, the existence of $\pi'^\pm$ or $H^\pm$ in the small triangular region at low mass and high B_τ values is also excluded. Summarizing, we can say that the existence of technipions or charged Higgs particles is excluded for masses between 6 and 14 GeV and branching ratios B_τ larger than 10%. This result severely restricts extended technicolor models.

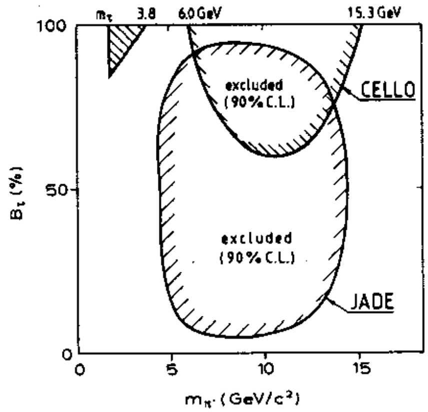


Fig. 11: 90% C.L. limit of the branching ratio B_τ as a function of the mass $m_{\pi'}$ of a technipion or charged Higgs-particle determined by CELLO[26] and JADE[1].

SUMMARY

Intensive searches for new particles have been made at PETRA with the following results:

1. No new quark, confined or free, with charges $Q = 2/3$ and $1/3$ has been detected up to $\sqrt{s} = 36.7$ GeV.
2. No new leptons such as a charged heavy lepton, an excited electron or muon, a stable charged lepton or a heavy neutral electron have been found.
3. No fundamental scalar or pseudoscalar particles such as the supersymmetric partners of the leptons, charged Higgs particles or technipions have been observed.

The existence of most of the particles is excluded for masses smaller than about 15 GeV. This value reflects the c.m. energy of about 35 GeV, at which PETRA has been running. At the end of the year 1982 the energy of PETRA will be raised to 41 GeV. Clearly the search for new particles will continue and lets hope that we find one.

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