RECENT TESTS OF QUANTUM-FLAVORDYNAMICS AT PETRA

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ABSTRACT

Recent tests of Quantum-Flavordynamics (QFD) from all PETRA experiments are reviewed. Pure QED has been tested in $e^+e^- \to \gamma\gamma$ and effects of the weak neutral current (NC) have been searched for in the reactions $e^+e^- \to \ell^+\ell^-$ and $q\bar{q}$. QED adequately describes the data up to $q^2 \gtrsim 1000$ GeV^2, demonstrating that charged leptons (including τ) have a radius smaller than $\sim 10^{-3}$ f. The non-observation of weak effects in e^+e^- interactions at PETRA puts stringent limits on the parameters of the weak neutral current. In particular, PETRA and neutrino electron scattering results taken together determine the coupling constants of the leptonic NC from purely leptonic interactions alone. The data support the hypothesis that the neutral current can be described in terms of a single parameter, $\sin^2\theta_W$. Alternatives to the standard SU(2) x U(1) model of electroweak interactions are constrained by the PETRA data.

I. INTRODUCTION

Tests of impressive precision have been and are still being performed that have demonstrated that QED is the theory to describe electromagnetic interactions of leptons at low momentum transfer (q^2)[1]. The weak neutral current (NC) has first been observed in lepton-lepton scattering[2], its couplings to leptons and quarks have been studied at low and medium q^2 [3,4] and its properties have been shown to be very well described by the standard SU(2) x U(1) theory (GWS)[5] in terms of a single parameter, $\sin^2\theta_w$. The interference of weak and electromagnetic interactions, however, has so far only been established in the scattering of polarized electrons off deuterium[6]. Electroweak interference is expected to cause small but measurable deviations from QED in $e^+e^- \rightarrow \ell^+\ell^-$ at very high q^2. Observation of this effect in lepton-lepton interactions would provide an ideal test of electroweak theories since no internal structure of projectile of target enters into the interpretation of the results.

The questions to be answered by data from PETRA are therefore twofold:

- Is pure QED for pointlike particles still sufficient a theory to describe the data at q^2 up to 1350 GeV^2?
- Do electroweak effects become visible and what can be learned about the weak NC in high momentum transfer reactions?

These questions have been attacked by all experiments that have taken data at the e^+e^- storage ring PETRA in Hamburg, Germany: CELLO, JADE, MARK-J, PLUTO and TASSO. This report is based on recent and partially unpublished results by all these groups and contains data taken at c.m. energies ($\sqrt{s}$) between 12 and 36.6 GeV. Descriptions of the apparatus'and data analysis methods have been published [7-11] and will not be treated here. A common stategy has, however, been adopted by the PETRA groups in order to make their results directly comparable:

The data are fully corrected for acceptance and detector effects. Radiative corrections are applied in the form of Monte Carlo calculations[12] which are accurate to order α^3 and contain virtual and real bremsstrahlung from initial and final state as well as vacuum polarization by electron, muon, tau and quark loops. The data corrected in this way are thus directly comparable to the lowest order QED predictions and deviations expected from a given physics hypothesis are easy to parametrize. The hypotheses we will consider here are:

1) QED breaks down at a scale Λ. This would be visible already at q^2, $s \ll \Lambda^2$ as a form factor which modifies propagators or lepton vertices.
2) In addition to the photon, the Z^o takes part in mediating e^+e^- interactions. This modifies the QED cross sections according to electroweak theories.

In principle, these two hypotheses have to be tested simultaneously. Systematic and statistical uncertainties in the data, however, only allow for separate tests until now.

2. $e^+e^- \to \gamma\gamma$

This reaction is unique in that it is a pure QED process at present energies. The lowest order diagrams contributing are shown in Fig. 1. Weak interactions only come into play to 4^{th} order of the coupling constant. The differential cross section $d\sigma/d\Omega$ for this process has been measured by all five PETRA groups. Like all QED cross sections it is usually presented in the form $s \cdot d\sigma/d\Omega$ to take out the $1/s$ dependence expected for pointlike particles interacting. The data taken at different c.m.energies are then readily combined. Fig. 2 shows recent

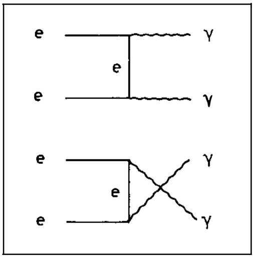

Fig. 1

Lowest order QED Feynman diagrams for $e^+e^- \to \gamma\gamma$.

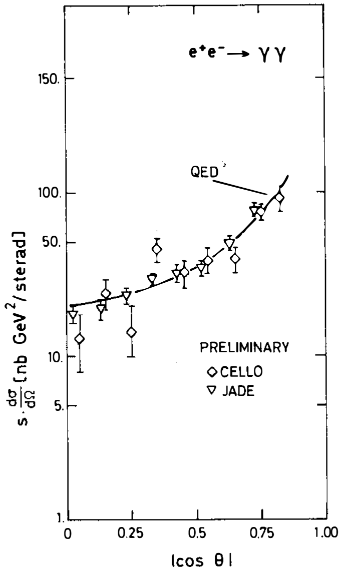

Fig. 2

The angular distribution for $e^+e^- \to \gamma\gamma$ measured by CELLO and JADE at $s \simeq 35$ GeV compared to the QED prediction (solid line).

results obtained by the CELLO and JADE groups. The data are in good agreement with the QED predictions but statistical errors are still relatively big. Agreement with QED is made quantitative by introduction of formfactors into the theoretical cross section. In the case of $e^+e^- \to \gamma\gamma$ a formfactor parametrizing breakdown of QED has the form[13]

$$F(Q^2) = 1 \pm q^4/\Lambda_\pm^4 \qquad (1)$$

It depends on the cutoff parameter Λ only to the 4^{th} power since propagator effects usually present cancel here because of current conservation in fermion exchange. Data are compatible with $\Lambda \to \infty$, i.e. pure QED for pointlike particles. Experiments therefore give 95% CL lower bounds on Λ that are summarized in Table I.

Another physics hypothesis testable here is the exchange of a heavy particle e^* with the quantum numbers of the electron. In this case the differential cross section would be modified by a factor δ_{e^*} [14]

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{QED} (1 + \delta_{e^*})$$
$$\delta_{e^*}(s, \theta) = \pm \; s^2 \sin^2\theta_w / 2\Lambda'^4_{\pm} \qquad (2)$$

where θ is the scattering angle.

Lower limits on Λ' are again given in Table I. The limit Λ'_+ can be interpreted as lower limit on the mass of the e^* if its coupling to the photon is the same as for the ordinary electron.

	Λ_+	Λ_-	
MARK-J	51	41	prelim.
PLUTO	46	36	
	Λ'_+	Λ'_-	
CELLO	43	48	prelim.
JADE	47	44	
MARK-J	51	49	prelim.
PLUTO	46	-	
TASSO	34	42	

Table I

Cut-off parameters for $e^+e^- \to \gamma\gamma$. Λ corresponds to a formfactor ansatz, Λ' to heavy electron exchange. All numbers are 95% CL lower limits.

3. $e^+e^- \to \ell^+\ell^-$

The lowest order weak and electromagnetic contributions to Bhabha scattering, muon pair and tau pair production are shown in Fig. 3. Fig. 4 shows the total cross sections for $e^+e^- \to \mu^+\mu^-$ and $\tau^+\tau^-$ as a function of the c.m. energy. The data agree well with the prediction ($p_\ell >> m_\ell$)

$$\sigma_{QED} = 4\pi\alpha^2/3s \qquad (3)$$

for pointlike particle production, which is especially remarkable for the heavy

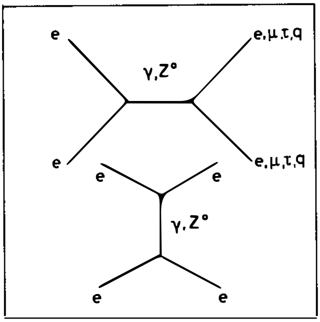

Fig. 3

Lowest order weak and electromagnetic contributions to $e^+e^- \to \ell^+\ell^-$ and $q\bar{q}$.

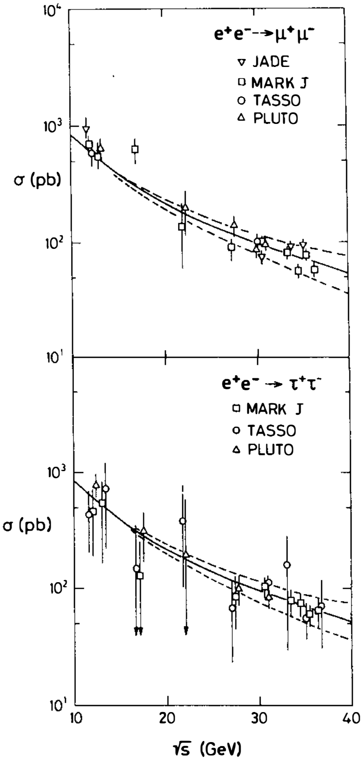

Fig. 4

Total cross sections for $e^+e^- \to \mu^+\mu^-$ and $\tau^+\tau^-$ measured at PETRA. The solid line represents the QED predictions, the upper and lower dashed curves correspond to $\Lambda_+=100$ GeV and $\Lambda_-=100$ GeV, respectively.

lepton τ. Deviations from this pointlike behaviour are parametrized by introducing formfactors

$$F_s(q^2) = 1 \mp q^2/(q^2 - \Lambda^2_{s\pm})$$
$$F_t(s) = 1 \mp s/(s - \Lambda^2_{t\pm}) \qquad (4)$$

in the timelike and the spacelike region, which modify lepton vertices or propagators. For simplicity we will assume $\Lambda_s = \Lambda_t \equiv \Lambda$. As mentioned above, we will neglect all weak effects in determining lower limits for Λ. A cut-off parameter of 100 GeV will then lead to a 10% modification of the total cross section at high $\sqrt{s}$, which is a presently accessible experimental accuracy (see Fig. 4).

Again, all data are compatible with $\Lambda \to \infty$, i.e. pure QED is sufficient to describe the data up to the highest energies reached so far. Lower limits on the cut-off parameters are given in Table II.

	Λ_+	Λ_-		
CELLO	90	145	prelim.	
JADE	112	106		
MARK-J	96	179	prelim.	$e^+e^- \to e^+e^-$
PLUTO	80	234		
TASSO	150	136		
JADE	142	126	prelim.	
MARK-J	194	153	prelim.	$e^+e^- \to \mu^+\mu^-$
PLUTO	107	101		
TASSO	80	118		
MARK-J	126	116	prelim.	$e^+e^- \to \tau^+\tau^-$
PLUTO	79	63		
TASSO	88	103	prelim.	

Table II

Cut-off parameters for $e^+e^- \to \ell^+\ell^-$. All numbers are 95% CL lower limits for $\Lambda_s = \Lambda_t \equiv \Lambda$.

They reach 150 GeV in the case of Bhabha scattering and muon pair production and more than 100 GeV for tau pair production. Transformed into coordinate space, limits on the cut-off parameters represent limits on the charge radius r of the "naked" leptons. For all known leptons, including τ, r is measured to be less than about 10^{-3}f.

4. TESTS OF ELECTROWEAK THEORIES WITH $e^+e^- \to \ell^+\ell^-$

Since we have not observed any deviation from QED whatsoever, we will in the following assume exact validity of QED and pointlike leptons ($\Lambda \to \infty$). This will allow us to determine how big the coupling constants of the weak NC can possibly be without PETRA experiments observing its effects. The first hypothesis we can test is that the exchange of a single neutral intermediate boson (Z^0) interferes with the normal one photon exchange reaction (see Fig. 3). We will assume that the weak NC consists of (Lorentz-) vector and axial vector pieces only, as determined recently by low energy neutrino experiments[15] and that it couples to leptons in a universal manner. Its effective Lagrange operator for e^+e^-

annihilation can then be written in terms of three coupling constants h_{VV}, h_{VA} and h_{AA} [16, 17] coupling leptonic vector currents to vector currents, vector to axial vector currents and axial vector to axial vector currents. The factorization hypothesis relates these couplings to those determined in neutrino electron scattering, g_V and g_A [17]

$$\begin{aligned} h_{VV} &= k^2 g_V^2 \\ h_{AA} &= k^2 g_A^2 \\ h_{VA} &= k^2 g_V g_A \end{aligned} \qquad (5)$$

where k is a model dependent constant [17] we will assume to be one as e.g. in the GWS model. As mentioned above, the GWS model describes all couplings as a function of the electroweak mixing parameter, $\sin^2\theta_w$

$$\begin{aligned} h_{VV} &= 1/4\ (1-4\ \sin^2\theta_w)^2 \simeq 0.002 \\ h_{AA} &= 1/4 \\ h_{VA} &= 1/4\ (1-4\ \sin^2\theta_w) \simeq 0.020 \end{aligned} \qquad (6)$$

where the numbers given correspond to $\sin^2\theta_w \simeq 0.23$ as measured in νq scattering [4]. These values of the coupling constants correspond to a nearly pure axial vector weak NC. The effects in the observed cross sections for $e^+e^- \to \ell^+\ell^-$ from the standard model are thus small. The deviations δ_w in

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}'_{QED}\ (1+\delta_W) \qquad (7)$$

reach maximally 3% at $\sqrt{s} \simeq 35$ GeV since they are proportional to h_{VV}. The dependence of the cross section on the scattering angle θ (the angle between the incoming e^- and the outgoing ℓ^-) will, however, no longer be symmetric around $\theta = 90^o$ for muon and tau pair production as it is for lowest order QED (Fig. 5). The charge asymmetry A

$$A = \frac{F - B}{F + B} \qquad (8)$$

where F and B are the number of negative muons or taus scattered into the forward and backward hemisphere with respect to the e^-, will differ from zero by about -7%, its value being proportional to h_{AA}. These small effects are at the very limit of current statistical and systematic accuracy of PETRA experiments.

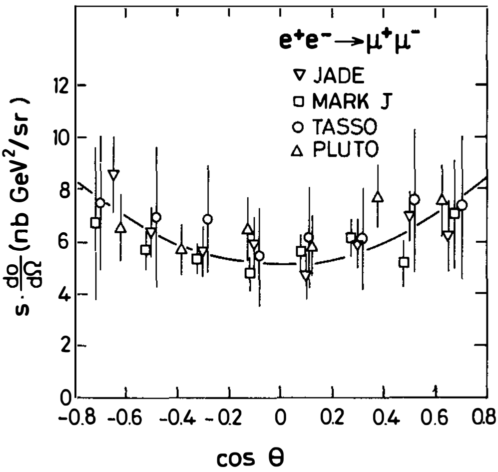

Fig. 5

Angular distribution of muon pair production measured at PETRA. The solid line is the prediction of QED, $(1 + \cos^2\theta)$.

Table III shows the measured charge asymmetries from JADE, MARK-J, PLUTO and TASSO (integrated over each experiment's acceptance and corrected for higher order QED contributions) compared to the expectation from the GWS theory. The combined result from the PETRA experiments yields

$$\langle A_{\mu\mu} \rangle = -(2.8 \pm 3.4)\% \tag{9}$$

compatible with zero, i.e. lowest order QED, as well as -6.7% as predicted by the standard model ($\sin^2\theta_W = 0.23$). Also given in Table II is the asymmetry for tau pair production from MARK-J and TASSO. For its average

$$\langle A_{\tau\tau} \rangle = -(3 \pm 8)\% \tag{10}$$

the same conclusion holds although the measurement is less accurate because of limited acceptance. We thus conclude that in agreement with both QED and the GWS theory no significant charge asymmetry has been observed at PETRA so far. The factorization hypothesis relates the asymmetries to the weak NC coupling constants g_A for electron, muon and tau. Giving up lepton universality for a moment, we have

$$A_{\mu\mu,\tau\tau} = g_A(e)\; g_A(\mu,\tau) \tag{11}$$

Assuming $g_A(e) = 1/2$ we can infer an upper limit on g_A for muon and tau

$$\left.\begin{aligned} g_A(\mu) &\le 0.72 \\ g_A(\tau) &\le 1.62 \end{aligned}\right\} \quad 95\%\ \text{CL} \tag{12}$$

	Observed	Expected (GWS)		
JADE	$-(5\pm6)\%$	-6%		
MARK-J	$-(1\pm6)\%$	-7.7%	prelim.	$e^+e^- \to \mu^+\mu^-$
PLUTO	$+(7\pm8\pm2)\%$	-5.8%		
TASSO	$-(6\pm8)\%$	-6.6%	prelim.	
MARK-J	$-(6\pm12)\%$	$\simeq-5\%$	prelim.	$e^+e^- \to \tau^+\tau^-$
TASSO	$(0\pm11)\%$	$\simeq-7\%$	prelim.	

Table III

Observed and expected weak charge asymmetries in the PETRA experiments. The experimental results are corrected for detector and radiative effects. The GWS expectation corresponds to $\sin^2\theta_W = 0.23$ and is integrated over the detector acceptance.

This demonstrates that at least for the muon the axial vector coupling cannot be significantly bigger than 1/2.

Severe limits on the vector part of the NC are provided by the measured large angle Bhabha scattering cross sections. Fig. 6 shows the results from all

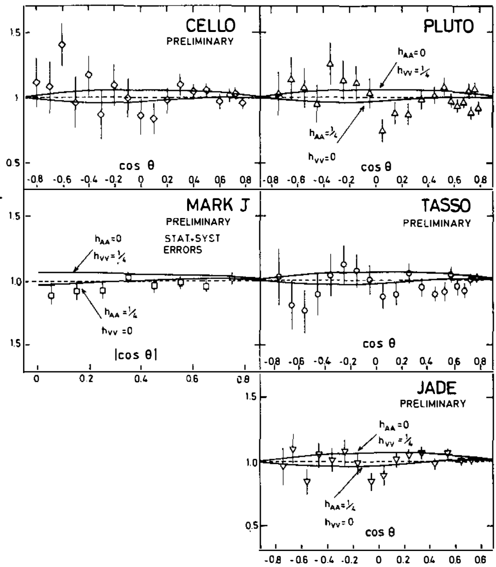

Fig. 6

The measured angular distribution of Bhabha scattering relative to the lowest order QED prediction. The curves correspond to pure QED (dashed line), a pure vector (upper solid curve) and a pure axial vector weak NC (lower solid curve). The errors are purely statistical, except for MARK-J (see text).

five PETRA experiments compared to two extreme hypotheses, a pure vector (h_{AA} = 0, h_{VV} = 1/4) and a pure axial vector (h_{VV} = 0, h_{AA} = 1/4), weak neutral current. It is clear, especially for the MARK-J data which contain the full statistics of the 1980 PETRA running (≃ 200 K events) and take into account systematic errors, that the first alternative is incompatible with the data. A pure vector current would give a positive deviation from QED which is not observed.

Table IV gives the limits set by the data on the electroweak mixing parameter, $\sin^2\theta_w$, if interpreted in terms of the GWS theory. Since $\sin^2\theta_w$ = 1/4 predicts the smallest deviation from QED, the best fit naturally turns out to be in the vicinity of 1/4 and 68% CL limits only are given. Also listed is the experimental information used in this determination by each experimental group. It ranges from Bhabha scattering only (CELLO) to all leptonic data mentioned above (MARK-J). Systematic errors taken into account and included in the limits are given in the table. All groups assign an error of about 4% to the overall normalization of cross sections. This normalization comes from the luminosity measurement by small angle Bhabha scattering, where weak effects are expected to be negligible. The MARK-J group in addition assigns an uncorrelated systematic error of 3% to each point in their differential Bhabha cross section to account for uncertainties in the determination of the scattering angle.

	Limits on $\sin^2\theta_w$ 68% CL	Information used	Syst. Errors included
CELLO	$0.10 \geq \sin^2\theta_w \geq 0.40$	e^+e^- only	Norm. 3%
JADE	$0.10 \geq \sin^2\theta_w \geq 0.40$	e^+e^-, $\mu^-\mu^+$, $A_{\mu\mu}$	Norm. 5%
MARK-J	$0.12 \geq \sin^2\theta_w \geq 0.36$	e^+e^-, $\mu^-\mu^+$, $\tau^+\tau^-$, $A_{\mu\mu}$	Norm. 3%, e^+e^- 3% uncorrelated
TASSO	$0.13 \geq \sin^2\theta_w \geq 0.35$	e^+e^-, $\mu^+\mu^-$, $A_{\mu\mu}$	Norm. 4%

Table IV

Experimental limits in $\sin^2\theta_w$ at 68% CL. The information used and the systematic errors included by each group are given.

Giving up the constraint that all couplings of the weak NC are described by a single parameter, fits can be performed to determine h_{VV} and h_{AA} separately. Fig. 7 quotes the results for JADE, MARK-J, PLUTO and TASSO together with the 68% CL errors. They all are compatible with pure QED (h_{VV} = h_{AA} = 0) and with the GWS prediction for $\sin^2\theta_w$ ≃ 1/4 (h_{VV} ≃ 0, h_{AA} = 1/4). The factorization hypothesis allows us to convert the limits in the quadrant h_{VV}, $h_{AA} > 0$ into limits on g_V and g_A and to compare them to those obtained in neutrino electron scattering. So far, this has only been done by the MARK-J group and Fig. 8 shows the results. The limits defined by the neutrino experiment at 68% CL appear as

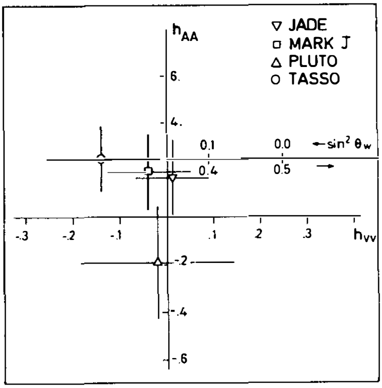

Fig. 7
Best fit values for h_{VV} and h_{AA} and their uncorrelated 1σ errors from the PETRA experiments using data and systematic errors as listed in Table IV.

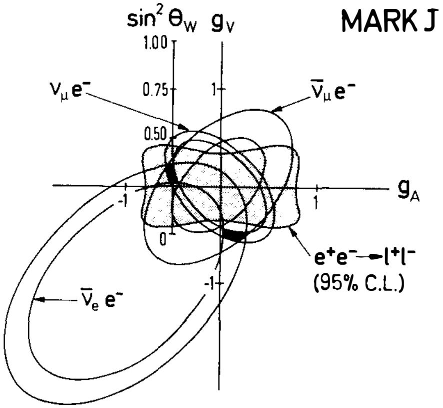

Fig. 8
Limits in g_V and g_A obtained from the MARK-J data on $e^+e^- \to \ell^+\ell^-$ and from $\overset{(-)}{\nu} e^-$ scattering. Regions in between the concentric ellipses correspond to 68% CL limits from the $\overset{(-)}{\nu}$ experiments, the two black areas indicate their overlap. The shaded domain is the region allowed by the e^+e^- data to 95% CL.

elliptical rings in the g_V/g_A plane intersecting in two narrow regions. One of these regions corresponds to a pure vector NC ($g_V \simeq -1/2$, $g_A \simeq 0$), the other one to the GWS solution ($g_V \simeq 0$, $g_A \simeq -1/2$). The MARK-J data exclude the pure vector NC with more than 95% CL. This conclusion is still valid when the regions allowed by $\overset{(-)}{\nu} e^-$ scattering are determined to 95% CL and it can be reached with the MARK-J data on $e^+e^- \to e^+e^-$ only. The coupling constants of the leptonic weak neutral current are thus determined by lepton-lepton scattering alone to be in agreement with the GWS theory for $\sin^2\theta_w \simeq 1/4$.

We therefore conclude that PETRA data strongly support todays viewpoint on the leptonic weak neutral current: it is dominated by its axial vector component and couples to all known leptons in a universal and q^2 independent manner well described by the GWS theory of weak and electromagnetic interactions.

5. WEAK EFFECTS IN $e^+e^- \to$ hadrons

Z^o exchange should also contribute to multihadron production in e^+e^- annihilation (Fig. 3). The contribution of quark flavor i to the total cross section of $e^+e^- \to q\bar{q}$ can be written as[18]

$$R = \frac{\sigma(e^+e^- \to \gamma, Z^o \to q_i\bar{q}_i)}{\sigma_p} = 3 \Big[Q_i^2 - 8Q_i \; s \; g_V g_{V_i} G \; p(s) + 16 \; s^2 G^2 (g_V^2 + g_A^2)(g_{V_i}^2 + g_{A_i}^2) \; p'(s) \Big] \tag{13}$$

where $\sigma_p = 4\pi\alpha^2/3s$ denotes the lowest order point-like QED cross section for $e^+e^- \to \mu^+\mu^-$, Q_i is the charge of the quark q_i, g_V and g_A are the weak coupling constants of the electron and g_{V_i}, g_{A_i} are those of the quark:

$$g_{V_i} = \begin{cases} 1/2 - 8/3 \sin^2\theta_w & \text{for u and c quarks} \\ -1/2 + 4/3 \sin^2\theta_w & \text{for d, s, and b quarks} \end{cases}$$

$$g_{A_i} = \begin{cases} +1/2 & \text{for u and c quarks} \\ -1/2 & \text{for d, s, and b quarks} \end{cases} \tag{14}$$

The propagator terms are

$$p(s) = \Big[(s/M_Z^2 - 1) + \Gamma_Z^2/(s-M_Z^2) \Big]^{-1} \tag{15}$$

for the interference term and

$$p'(s) = \Big[(s/M_Z^2 - 1)^2 + \Gamma_Z^2/M_Z^2 \Big]^{-1} \tag{16}$$

for pure Z^o exchange, and

$$G \equiv G_F/(8\sqrt{2}\,\pi\alpha) \simeq 4.49 \quad 10^{-5} \; \mathrm{GeV}^{-2}$$

The total cross section R is then given as an incoherent sum of the R_i over all flavors and has to be corrected for gluon contributions[19]

$$R = R_i \Big[1 + \alpha_s/\pi + (1.98 - 0.115 \; N_f) \; \alpha_s^2/\pi^2 \Big] \tag{17}$$

where N_f is the number of flavors contributing. α_s is the strong coupling constant which has been measured to be about 0.18 at $\sqrt{s} \simeq 33$ GeV [20 - 23]. R then becomes a function of g_{V_i} and g_{A_i}. Interpreting the data in terms of the GWS theory one sets limits on $\sin^2\theta_w$ again. The preliminary results from the MARK-J group are

$$0.12 < \sin^2\theta_w < 0.65 \qquad (95\%\ \mathrm{CL}) \qquad (18)$$

using the total cross sections measured between $\sqrt{s}$ of 12 and 36.6 GeV[24] and including a systematic error of 10% in the absolute normalization.*) Although the accuracy of this result is clearly inferior to that recently obtained in neutrino scattering [4] it lends important support to the hypothesis that the weak NC can indeed be described by a single parameter. Note that these limits on the coupling of the hadronic NC are again obtained at very high q^2 and that about 40% of the multihadron events entering this study have a heavy quark (c, b) in the primordial final state. Semileptonic neutrino interactions on the other hand are studied at comparatively low q^2 and involve essentially nothing but valence u and d quarks present in the nucleons. The PETRA data[26] thus provide a first indication that the weak neutral current also couples to all known quarks, light as well as heavy, in the universal, q^2 independent manner predicted by the standard electroweak theory.

6. ALTERNATIVE ELECTROWEAK MODELS

There are, however, alternatives which are constructed so as to preserve the successes of the GWS scheme and still yield observable differences in the high q^2 region. Those models are based on a larger basic symmetry group SU(2) x U(1) x G and thus add a piece analog to electromagnetism to the effective Hamiltonian[27]

$$H_{eff}^{NC} = \frac{4\,G_F}{\sqrt{2}} \left(J_3 - \sin^2\theta_w\, J_{em}\right)^2 + c\, J_{em}^2 \qquad (19)$$

with the weak neutral current J_3 and the electromagnetic current J_{em}. Such a modification leaves $\overset{(-)}{\nu}q$ and $\overset{(-)}{\nu}e^-$ scattering unchanged, since it only concerns the electromagnetic current. It also leaves polarized electron scattering off quarks unchanged since the additional interaction conserves parity. The coupling constants of the leptonic NC in such a model can be written as[27-29]

$$\begin{aligned} h_{VV} &= 1/4\ (1-4\sin^2\theta_w)^2 + 4c \\ h_{AA} &= 1/4 \\ h_{VA} &= 1/4\ (1-4\sin^2\theta_w) \end{aligned} \qquad (20)$$

*) Similar results have been obtained by JADE[25].

where $\sin^2\theta_w$ stands for the electroweak mixing parameter measured at low q^2. The distinctive feature of these models is that they have more than one neutral intermediate boson in addition to the photon. Two specific models of this kind have been considered in detail:

The model of de Groot et al.[28] covers the case G = U´(1) and thus has two Z^o's with masses

$$m(Z_1^o) < M(GWS) < m(Z_2^o) \qquad (21)$$

where

$$M^2\ (GWS) \equiv 2\sqrt{s}\ \pi\alpha/(G_F \sin^2 2\theta_w)$$

in addition to a single charged boson pair $W^\pm$. The model of Barger et al. considers G = SU´(2) and thus gives two Z^o's with two $W^\pm$ pairs[29]. The constant c in front of the additional contribution to the Hamiltonian measures the mass splitting between the two Z^o's:

Upper Limit on c (95% CL)		
JADE	0.039	
MARK-J	0.032	prelim.
PLUTO	0.06	
TASSO	0.03	prelim.

Table V

Upper limits on the mass splitting parameter c at 95% CL. All limits assume $\sin^2\theta_w = 0.23$ and include the systematic errors quoted in Table IV.

$$c = \frac{(m_2^2 - M_{GWS}^2)\ (M_{GWS}^2 - m_1^2)}{m_1^2\ m_2^2} \cdot \begin{cases} \cos^2\theta_w & \text{for } G = U'(1) \\ \sin^2\theta_w & \text{for } G = SU'(2) \end{cases} \qquad (22)$$

Since it enters into h_{VV}, the measurement of this constant allows to set a limit on c. Table V summarizes these limits obtained by the PETRA experiments assuming $\sin^2\theta_w = 0.23$. Using relation (22), they can be converted into allowed regions for m_1, m_2. This is shown in Fig. 8 for the example of the JADE data, results from other groups are very similar. One sees that at least for the model of de Groot et al., where the new interaction is relatively strongly coupled, the possible range for m_1 and m_2 is restricted to a tight band around $m_1 = m_2 = M_{GWS}$ where both models converse towards the GWS theory.

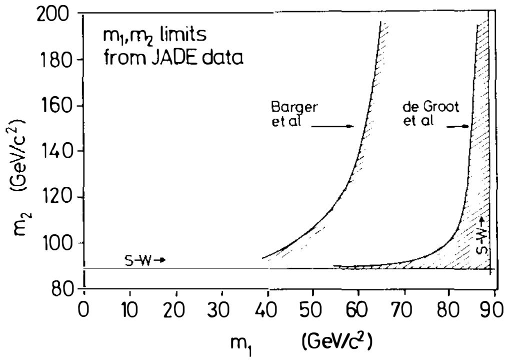

Fig. 9

Limits on m_1 and m_2 for models with two Z^o bosons as deduced from the limit on c measured by JADE. The shaded area is the range allowed by the data at 95% CL. Limits from other PETRA experiments are very similar

7. CONCLUSIONS

The recent tests of electroweak theories with data from the PETRA experiments thus answer our initial questions as follows:

1) Pure QED is a sufficient theory to describe $e^+e^- \to \gamma\gamma$, e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ up to $Q^2 \gtrsim 1000\ GeV^2$.

2) Leptons, including the heavy τ, are found to be pointlike with a charge radius smaller than $\sim 10^{-3}$ f.

3) The non-observation of weak effects puts tight constraints on the magnitude of the weak coupling constants.

4) Especially the coupling constants of the leptonic weak neutral current are uniquely determined by lepton-lepton scattering alone to be in agreement with the GWS theory.

5) Comparing data on $e^+e^- \to \ell^+\ell^-$ and $q\bar{q}$ as well as $\overset{(-)}{\nu}e^-$ and $\overset{(-)}{\nu}q$ scattering in different kinematic regions supports the hypothesis that the weak neutral current can be described by a single parameter, $\sin^2\theta_W$.

6) Constraints are put on alternative electroweak models involving more than one neutral intermediate boson.

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