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by

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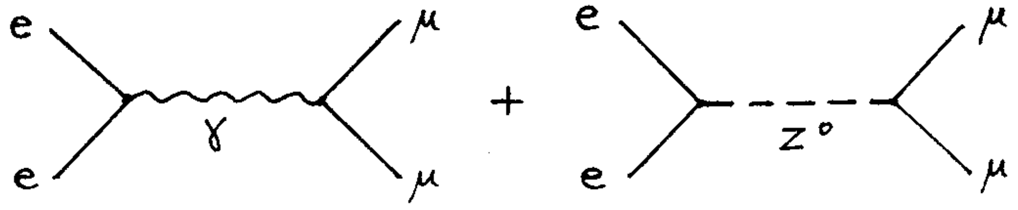
ABSTRACT

Recent experimental results on electro-weak interference are reviewed. New data come mostly from e^+e^- experiments at PETRA and PEP. The precise measurements of leptonic reactions are used to determine the weak neutral current parameters and to test the pointlike nature of leptons. Attempts are also made to extend these studies to the reaction $e^+e^- \rightarrow q\bar{q} \rightarrow$ hadrons with the aim of measuring the weak neutral current couplings of heavy quarks. The review includes a brief discussion of the search for new particles and limits on alternative models to the standard electroweak theory.

1. INTRODUCTION

Reactions of charged leptons with leptons or with quarks are dominated by the electro-magnetic interactions. In using these reactions to measure the effects of weak neutral currents we must study the interference between the electro-magnetic and weak interaction, since the contributions of the weak interaction alone are unmeasurably small. With our current understanding of the electroweak force we describe the electroweak interference as an interference between the photon and the Z^0 exchange as indicated for the reaction $e^+e^- \rightarrow \mu^+\mu^-$.



Plenary Talk at the Int. Europhysics Conf. on High Energy Physics, Brighton/U.K., July 1983.

The strength of the photon exchange is characterized by the fine structure constant, the strength of the Z^o exchange by the Fermi coupling constant $G = G_\mu = 1.166 \cdot 10^{-5}\text{GeV}^{-2}$.

In general the cross section contains three terms

$$\frac{d\sigma}{d\Omega}\,(\text{QED}) + \frac{d\sigma}{d\Omega}\,(\text{Interference}) + \frac{d\sigma}{d\Omega}\,(\text{weak}) \qquad (1)$$

which are proportional to

$$\sim \frac{\alpha^2}{s} \qquad \sim \alpha G \qquad \sim G^2 s \qquad (2)$$

We see that the size of the interference term relative to the QED contribution is of order $\frac{G}{\alpha}$ s and rises with s, the square of the c.m. energy. We must therefore measure at the highest possible energies in order to detect the electroweak interference. At low energies one separates the electroweak interference from higher order QED or strong interaction contributions by measuring parity violating effects. This can be seen from Table I, which lists the different types of electroweak interference experiments and their corresponding range of momentum transfer. The electron-deuterium scattering experiment$^{(1)}$ at SLAC and the atomic physics experiments$^{(2,3,4)}$ measure at low momentum transfer squared of about a few GeV^2 or a few MeV^2, respectively, and search for parity violating effects.

TABLE I

EXPERIMENTAL OBSERVATION OF ELECTROWEAK INTERFERENCE

Experiment	Q^2 range	observed effect
long. pol. e-deuterium scattering$^{(1)}$	1-2 GeV^2	parity violating
atomic physics experiments$^{(2,3)}$	few MeV^2 (see Ref. 4)	parity violating
long. pol. μ-carbon scattering$^{(5)}$	15-180 GeV^2	mainly parity conserving
$e^+e^- \to \ell^+\ell^-$ or $q\bar{q}$ at PETRA/DESY at PEP/SLAC	 $144 < s < 1850\ \text{GeV}^2$ $s = 841\ \text{GeV}^2$	no parity violation observed (unpol. e^+e^- beams)

The longitudinally polarised μ-carbon scattering experiment(5) which measures at Q^2 between 15 and 180 GeV^2 mainly detects a parity conserving effect and one is forced to calculate and to subtract large contributions from higher order QED. The situation is more favorable for the e^+e^- experiments owing to the high c.m. energies of the storage rings. Since the e^+, e^- beams are unpolarized there is no parity violation observed. However, the effect of electroweak interference rises with the c.m. energy squared and therefore dominates over the QED (α^3) contribution, which is practically energy independent. The QED radiative corrections can be precisely calculated(6) and one finds that these corrections are small, being typically about 20% of the electro-weak interference effect at a c.m. energy of 35 GeV.

2. ELECTROWEAK INTERFERENCE IN LEPTON-NUCLEON REACTIONS

Since there are no new results on charged lepton-nucleon scattering and on parity violation in atoms since the Paris Conference(2) I will mainly concentrate on the results from e^+e^- experiments. However, I should mention a contribution to this conference which discusses the theoretical implications of the recent observation of parity violation in atomic cesium(4). An analysis of the uncertainties of the theoretical calculations for the caesium atom leads to the result shown in Fig. 1. The caesium experiment(3,4) and the polarized e-d experiment(1) are sensitive to the electron-quark coupling $\varepsilon_{AV}(d)$ and $\varepsilon_{AV}(u)$ defined by the effective Lagrangian(7)

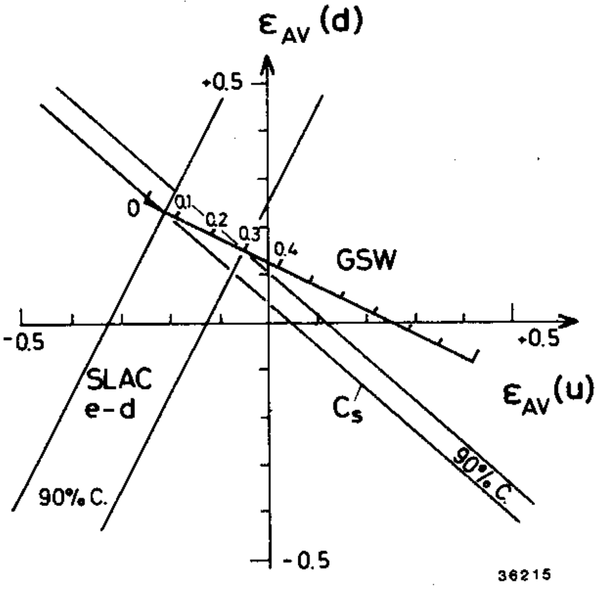


Fig. 1

Constraints (90% C.L.) on electron-quark couplings imposed by parity violation measurements in cesium(4) and by the SLAC e-d experiment(1).

$$L_{\text{eff}}(eq) = -\frac{G}{\sqrt{2}} \Big\{ \bar{e}\gamma e \left[\varepsilon_{VV}\bar{q}\gamma_\alpha q + \varepsilon_{VA}\bar{q}\gamma_\alpha\gamma_5 q\right] + \bar{e}\gamma_5\gamma_\alpha e \left[\varepsilon_{AV}\bar{q}\gamma_\alpha q + \varepsilon_{AA}\bar{q}\gamma_\alpha\gamma_5 q\right] \Big\} \qquad (3)$$

where q is the u or d quark. Fig. 1 shows the constraints with 90% confidence limits in the $\varepsilon_{AV}(u)$, $\varepsilon_{AV}(d)$ plane. The two experiments measure combinations of these coupling constants which are orthogonal to each other. The allowed regions meet at the line predicted by the GSW model and select a value of $\sin^2\theta \approx 0.2$. This is an important test of the GSW model obtained from a combination of experiments on electroweak interference at low q^2.

3. ELECTROWEAK INTERFERENCE IN e^+e^- EXPERIMENTS: GENERAL COMMENTS

The study of electroweak interference in e^+e^- annihilations has the following motivations:

(1) Neutral current couplings are measured relative to the electromagnetic current, which can be precisely calculated by QED.

(2) The electroweak theory is tested at very high q^2 and s, actually up to $q^2 \approx 1500$ GeV^2 and $s \approx 1800$ GeV^2.

(3) The measurements can be made with purely leptonic reactions, $ee \to ee$, $ee \to \mu\mu$ and $ee \to \tau\tau$, which correspond to the difficult measurements of the ν-e scattering.

(4) We can study the neutral current couplings of the charm and bottom quark, which are copiously produced at high energies via the reaction $e^+e^- \to q\bar{q} \to$ hadrons.

The results discussed here come from the experiments CELLO, JADE, MARK-J, PLUTO and TASSO at PETRA/DESY, and from HRS, MAC, and MARK II at PEP/SLAC. The e^+e^- storage ring at PETRA has been operating at a wide range of energies between 12 and 43 GeV. The high energy results are obtained from an integrated luminosity of about 50 to 80 pb^{-1} at an average energy of 35 GeV. The PEP storage ring has been running at a fixed c.m. energy of 29 GeV and has made a strong improvement in the luminosity. The experiments have collected a total integrated luminosity of about 150 pb^{-1}. Since this large data set is not fully analyzed, I report here results from a part of the data with luminosities between 60 and 100 pb^{-1}. We observe that PETRA and PEP have set different priorities for running. PEP has been running at 29 GeV optimizing the luminosity. PETRA has been continually increasing the machine energy in the search of the top quark with the consequence of having less luminosity. Nevertheless, at PETRA experiments have a considerable advantage over the PEP experiments for measuring electroweak interference, because the effects rise quadratically with energy. Note, that the electroweak effects at 43 GeV are 2.5 times larger than at 29 GeV!

4. SEARCH FOR NEW PARTICLES AT PETRA AND PEP

There have been extensive searches for new particles in high energy e^+e^- reactions. Many results are relevant to the theory of weak interactions and should briefly be mentioned here. More details can be found in a review by S. Yamada$^{(8)}$.

The PETRA experiments CELLO, JADE, MARK-J, and TASSO have recently been scanning in the energy range between 37.94 and 38.63 GeV and between 39.79 GeV and 43.18 GeV in steps of 30 MeV searching for a toponium resonance. No significant peak has been found in the hadronic cross section and the measurements exclude with 95% confidence the existence of a toponium resonance built up by quarks of charge 2/3 in this energy range.$^{(9)}$ In addition, no sign of a production threshold for a new quark of charge 2/3 or 1/3 has been found. The most stringent limits can be deduced from the thrust distribution of hadronic events which contain a prompt muon (Fig. 2). By selecting these events we enhance the top signal, since top quarks have a large probability to produce a lepton by their decay or by the subsequent cascade decays of bottom and charm, Fig. 2 clearly excludes the production of a new quark. When one tries to extract a mass limit there is some uncertainty due to the unknown threshold behaviour.

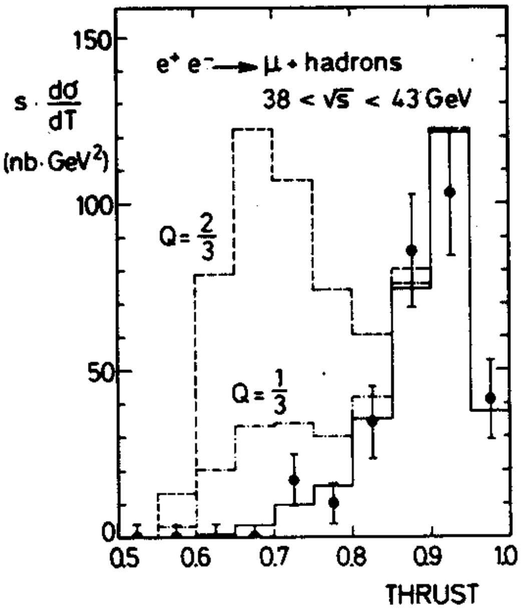


Fig. 2

Thrust distribution of events $e^+e^- \to \mu$ + hadrons measured by MARK-J between 38 GeV and 43 GeV. The measurements are compared to the prediction for 5 quarks u,d,s,c,b (solid line) and for six quarks with a top quark of charge 2/3 (dashed line) and of charge 1/3 (dashed-dotted line).

Therefore we prefer to say that the maximum increase in the hadronic cross section averaged over the energy range between 40 and 43 GeV is $\Delta R \leq 0.07$ with 95% confidence. This limit can be compared to a step of the hadronic cross-section of $\Delta R = 4/3$ or $1/3$ expected far above threshold for the production of a new quark with charge 2/3 or 1/3, respectively.

The recent high energy measurement at PETRA gives the experiments the opportunity to update the earlier limits(10) on new particle searches. No new heavy lepton is found, be it sequential, excited or stable(11). The existence of a sequential heavy lepton is excluded with 95% confidence by JADE and MARK-J for masses less than 20.6 GeV. A detailed search at CESR, PETRA and PEP for charged Higgs particles or technipion has shown that none exists with masses below 14 GeV irrespective of their branching into $\tau\nu$ or $c\bar{s}$ or $c\bar{b}$ (12). This limit has been extended by MARK-J to 16 GeV for branching ratios into $\tau\nu$ larger than 20%.

In the last years supersymmetry has attracted interest due to the fact that it is a candidate for unifying all interactions including gravity. Since it postulates a symmetry between bosons and leptons it predicts a large number of new particles. Despite a wide search none of these particles has been observed yet.(12,13,8) For example, the pair production of supersymmetric partners of leptons via $e^+e^- \to s_\ell \bar{s}_\ell$ can be excluded for masses smaller than 17 GeV. MAC (and MARK II) extend the mass limit of the supersymmetric electron to 24 GeV (22.4 GeV) by a study of virtual s_e exchange or single s_e production.

5. NEUTRAL CURRENT COUPLINGS OF LEPTONS

The reaction $e^+e^+ \to \ell^+\ell^-$ may be described in a model-independent way by three parameters. Following Hung and Sakurai(14) we call them h_{VV}, h_{VA} and h_{AA}. Clearly, if we assume that lepton universality of the weak neutral currents is valid, the parameters are identical for $\ell = e, \mu$ and τ. At high energies we have to introduce the Z^o masses as additional parameters.

In SU(2) x U(1) models these parameters are expressible in terms of the weak mixing angle $\sin^2\theta_w$ and T_{3L} and T_{3R}, the third components of the weak isospin of the left handed and right handed leptons.

$$
\begin{aligned}
h_{VV} &= \rho(T_{3L} + T_{3R} + 2\sin^2\theta_w)^2 \\
h_{AA} &= \rho(T_{3L} - T_{3R})^2 \\
m_Z^2 &= \frac{m_W^2}{\rho\cos^2\theta_w} = \frac{1}{\rho}\,\frac{\pi\alpha}{\sqrt{2}\,G_F}\,\frac{1}{\sin^2\theta_w\,\cos^2\theta_w}
\end{aligned}
\tag{4}
$$

The parameter ρ measures the strength of the weak neutral current interaction relative to the weak charged current interaction.

In the standard $SU(2)_L \times U(1)$ theory of GSW(15) the left-handed lepton fields are arranged in weak iso-doublets, and the right-handed lepton fields in weak iso-singlets. Since this theory also predicts $\rho = 1$, we get

$$
\begin{aligned}
h_{VV} &= g_V^2 = \frac{1}{4}(1 - 4\sin^2\theta_w)^2 \\
h_{AA} &= g_A^2 = \frac{1}{4}
\end{aligned}
\tag{5}
$$

The parameters h_{VV} and h_{AA} are often called g_V^2 and g_A^2 in e^+e^- experiments and we follow that usage. However, be aware that the symbols g_V and g_A are usually reserved for the coupling constants of ν-e scattering.

6. MEASUREMENTS OF LEPTONIC REACTIONS

We turn now to the measurements of leptonic reactions $e^+e^- \to \ell^+\ell^-$, where the lepton ℓ can be an electron, muon or tau. Descriptions of the experiments and details on the analysis can be found in the publications of the experiments(16-23). Leptonic reactions produce events with two mainly collinear back-to-back leptons, whose momenta are approximately equal to the beam momentum. For selection one typically requires the acollinearity angle ξ of the scattered leptons to be smaller than 10° and each lepton momentum to be larger than half the beam momentum. The radiative corrections to order α^3 are calculated for these cuts by the Monte Carlo program of Berends and Kleiss(6). All measurements presented here are corrected for QED radiative effects to order α^3 so that the data can directly by compared to the lowest order QED prediction.

6.1 RESULTS ON $e^+e^- \to e^+e^-$

We begin our discussion of individual leptonic reactions with Bhabha scattering, $e^+e^- \to e^+e^-$. Its measurement fulfills a twofold purpose: small angle Bhabha scattering serves as a luminosity monitor, while the angular distribution at large angles is sensitive to the weak interaction. The theoretical cross section$^{(24)}$ shows a rather complicated dependence on g_V^2 and g_A^2 because there are space-like and time-like exchanges of the virtual photon and the Z^o. Since the angular distribution falls very steeply and the deviations from QED are small, we present the data as the ratio of the measured cross section divided by the QED prediction.

All PETRA and PEP experiments perform measurements of Bhabha scattering. Fig. 3 shows two examples, the measurements of MARK J and MAC.

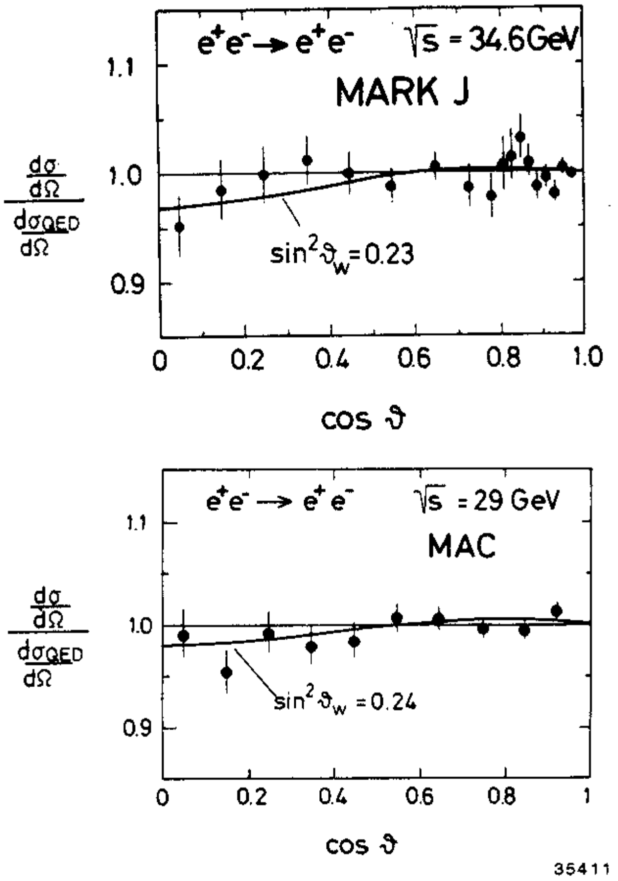


Fig. 3

Angular distribution of the reaction $e^+e^- \to e^+e^-$ measured by MARK J at PETRA and by MAC at PEP.

The angular distribution extends only to 90°, because both detectors do not distinguish electrons from positrons. In addition to the statistical errors shown in Fig. 3 there are point-to-point systematical errors of about 3% and an overall normalization error of 3%. We conclude from Fig. 3 and the measurements of other experiments that we cannot yet establish the effect of electroweak interference in Bhabha scattering because the difference between the predictions of pure QED and the GSW theory with $\sin^2\theta_W \approx 0.23$ is too small to be measurable with the actual experimental resolution.

6.2 CROSS SECTION OF $e^+e^- \to \mu^+\mu^-$

The cross section of $e^+e^- \to \mu^+\mu^-$ and analogously of $e^+e^- \to \tau^+\tau^-$ is given in QED by the pointlike cross section

$$\sigma_{pt} = \frac{4\pi\alpha^2}{3s} \quad . \tag{6}$$

The weak interaction predicts a small deviation from the pointlike cross sections due to the γ, Z interference

$$R_{\mu\mu} = \frac{\sigma_{\mu\mu}}{\sigma_{pt}} = 1 - 2\chi g_V^e g_V^\mu + \dots \tag{7}$$

where

$$\chi = \frac{\rho G_F}{2\sqrt{2}\,\pi\alpha} \; \frac{s \cdot m_Z^2}{m_Z^2 - s} \quad . \tag{8}$$

For simplicity I have omitted the purely weak term and neglected the width of the Z^o with respect to its mass. The variable χ is about 0.25 at $\sqrt{s}$ = 34.5 GeV if m_Z = 90 GeV. Hence the electroweak effect would be easily measurable if g_V^e and g_V^μ were to take the value of 1/2 as for the axial vector coupling. One would find a decrease of the muon pair cross section by 13%! The GSW theory, however, predicts

$$g_V^e \, g_V^\mu = \frac{1}{4} \left(1 - 4\sin^2\theta_w\right)^2 \tag{9}$$

which practically vanishes for $\sin^2\theta_w = 0.23$. Therefore, we do not expect to see an electroweak effect due to the vector coupling in $R_{\mu\mu}$. Clearly, we can reverse the reasoning: if we do not see an effect on $R_{\mu\mu}$, we know that $\sin^2\theta_w$ is near to 0.25. The errors are, however, quite large. If we were to find, for example, $R_{\mu\mu} = 1.00 \pm 0.02$ at 34.5 GeV, we would obtain $\sin^2\theta_w = 0.25 \pm 0.10$. This situation is typical of all e^+e^- reactions: electroweak effects connected to the vector coupling of leptons are difficult to measure and the errors on the determination of the weak mixing angle are large.

Fig. 4 summarizes the results on $R_{\mu\mu}$ from PETRA and PEP. The errors of the data points include statistical and systematical errors. The measurements agree well with the predictions of QED and of the GSW theory, which are practically undistinguishable for $\sin^2\theta_w = 0.23$. Since the weak interaction effects are small we can use these data to test QED. This is usually

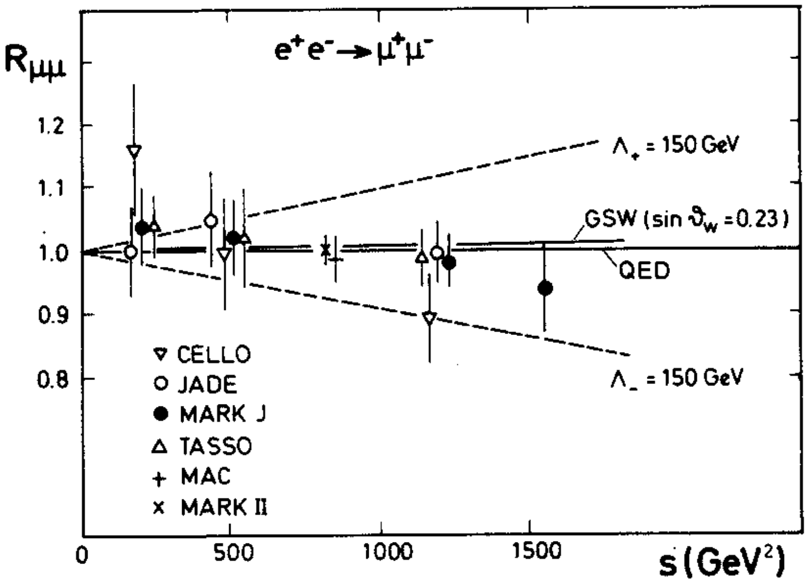


Fig. 4

Measurements of $R_{\mu\mu}$ from PETRA and PEP. The data are compared with the predictions of QED and of the GSW theory for $\sin^2\theta_W = 0.23$ (solid lines). The deviations from QED expected for cut-off parameter $\Lambda_\pm = 150$ GeV are also indicated (dashed lines).

done by introducing a form factor

$$F(q^2) = 1 \mp \frac{q^2}{q^2-\Lambda_\pm^2} \tag{10}$$

where we put $q^2 = s$ for the reaction $e^+e^- \to \mu^+\mu^-$. Lower limits of the cut-off parameter $\Lambda_\pm$ are determined comparing

$$\sigma = \sigma_{\mu\mu} F^2(s) \tag{11}$$

with the data. PETRA experiments find typical limits of 200 GeV with 95% confidence. Similar results can be obtained for electrons from $e^+e^- \to e^+e^-$ and for quarks from $e^+e^- \to q\bar{q} \to$ hadrons. This indicates that electrons, muons and quarks do not show any structure up to an energy scale of 200 GeV and interact, as if pointlike, down to a distance of 10^{-16} cm.

6.3 ASYMMETRY OF $e^+e^- \to \mu^+\mu^-$

The angular distribution of $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$ has the form

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\left[R_{\mu\mu}(1+\cos^2\theta) + B\cos\theta\right] . \tag{12}$$

The scattering angle θ is defined as the angle between the μ^- and the outgoing e^- beam. The factor

$$B = -4\chi g_A^e g_A^\mu + 8\chi^2 g_V^e g_V^\mu g_A^e g_A^\mu \tag{13}$$

depends mainly on the axial vector coupling and it determines the forward-backward asymmetry defined by

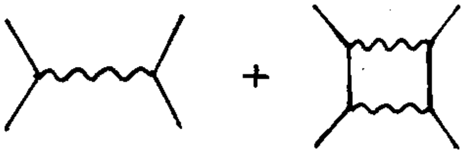
$$A_{\mu\mu} = \frac{N(\theta<90^o) - N(\theta>90^o)}{N(\theta<90^o) + N(\theta>90^o)} = \frac{3}{8}\,\frac{B}{R_{\mu\mu}} \quad . \qquad (14)$$

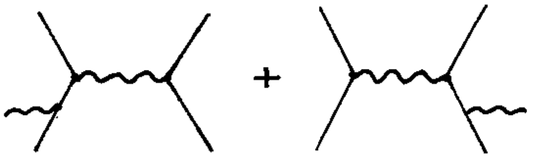
$N(\theta<90^o)$ is the number of events, where the μ^- is in the forward hemisphere, and $N(\theta>90^o)$ is the number of μ^- in the backward hemisphere. The asymmetry depends on the axial-vector couplings of the electron and muon and is practically independent of the vector coupling

$$A_{\mu\mu} = -\frac{3}{2}\,\frac{\chi g_A^e g_A^\mu (1-2\chi g_V^e g_V^\mu)}{(1-2\chi g_V^e g_V^\mu)} \approx -\frac{3}{2}\,\chi g_A^e g_A^\mu \quad . \qquad (15)$$

The asymmetry is negative at energies below the Z^o pole, if g_A^e and g_A^μ have the same sign. If we insert $g_A^e = g_A^\mu = -\frac{1}{2}$, $\rho = 1$ and $m_Z = 90$ GeV as predicted by the GSW theory, we expect an asymmetry of - 9.4% at $\sqrt{s} = 34.5$ GeV.

Pure QED also produces a forward-backward asymmetry by the interference of the one photon and two photon exchange graph and by the interference between initial and final state bremsstrahlung:





The QED asymmetry is much smaller than the electroweak asymmetry and it is positive. A Monte Carlo calculation(6) gives $A_{QED} = +1.5\%$ for $|\cos\theta| \leq 0.8$ and an acollinearity cut of 20°. All data presented here are corrected for QED(α^3) radiative effects. It is important to find out if there are additional electro-weak corrections to the asymmetry. A large amount of work(25) has been done in this field, but there is no unique answer yet. The general conclusion is that the electro-weak corrections, not due to QED, are small, and probably range between 0 and +0.7%. Therefore we neglect this problem for the moment and correct the data only for QED (α^3) radiative effects.

To measure the asymmetry one needs to determine the direction and the charge of the muons. The asymmetry can be measured very precisely, because it is a relative measurement, independent of the luminosity measurement. It is insensitive to errors in the acceptance and reconstruction efficiency as long as the acceptance is the same for positive and negative muons. For this reason, the experiments are able to limit the systematic error of the asymmetry to $\leq$ 1%. Furthermore, MARK J and MAC collected data in equal amounts with both magnet polarities thereby cancelling to the first order all systematic errors which relate to the charge measurement of muons. This leaves no doubt that the systematic error is much smaller than 1%.

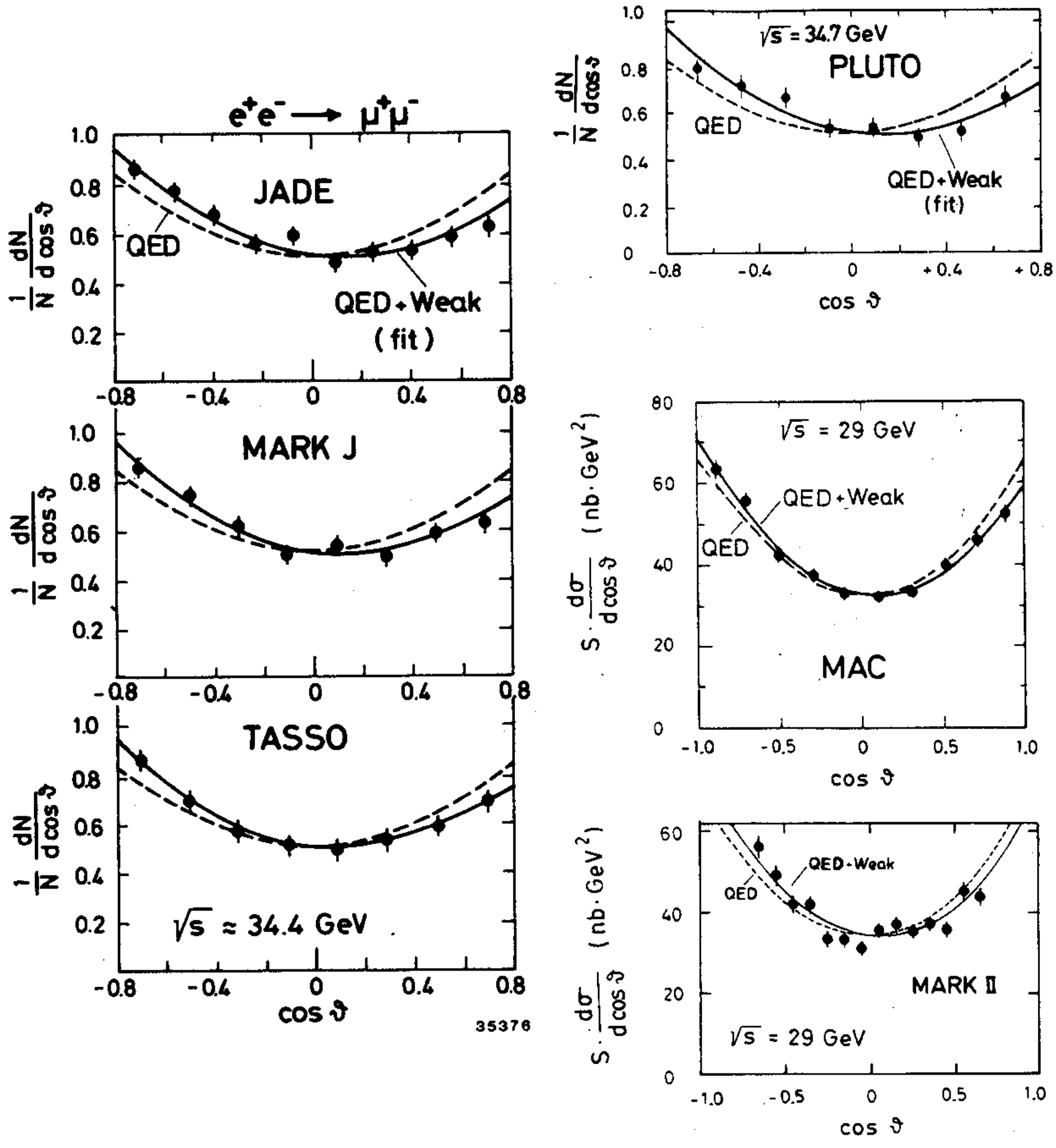


Fig. 5 Measurements of the angular distribution of $e^+e^- \to \mu^+\mu^-$ compared to the prediction of QED (dashed line) and to a fit including the weak interaction (solid line).

Fig. 5 shows the measurements of four PETRA experiments, JADE, MARK-J, PLUTO and TASSO, at $\sqrt{s} \approx 34.5$ GeV and of the MAC and MARK II experiment at PEP at $\sqrt{s} = 29$ GeV.

All measurements deviate from QED, which predicts a symmetric $(1+\cos^2\theta)$ distribution and show a significant negative asymmetry as predicted by the electroweak theory.

Table II summarizes the high energy measurements of the asymmetry. The systematic errors are estimated to be smaller than 1% and are included in

TABLE II

RESULTS FROM PEP AND PETRA ON THE ASYMMETRY OF $e^+e^- \rightarrow \mu^+\mu^-$ (16-23)

Experiment	$\sqrt{s}$ (GeV)	Measured $A_{\mu\mu}$ in %	Expected in GSW for $\sin^2\theta_W = 0.23$ in %
HRS	29	-8.4 ± 4.3	-6.3
MAC	29	-5.8 ± 1.0 ± 0.3	-6.3
MARK II	29	-8.0 ± 1.8 ± 0.8	-6.3
combined	29	-6.4 ± 0.9	-6.3
CELLO	34.2	-6.4 ± 6.4	-9.2
JADE	34.4	-11.0 ± 1.8 ± 1.0	-9.3
MARK J	34.6	-11.7 ± 1.7 ± 1.0	-9.5
PLUTO	34.7	-12.0 ± 3.2	-9.5
TASSO	34.5	-9.1 ± 2.3 ± 0.5	-9.5
combined	34.5	-10.8 ± 1.1	-9.4
JADE	40.3	-13.3 ± 6.0	-13.6
MARK J	39.8	-13.8 ± 6.3	-13.3
TASSO	41.2	-11.4 ± 10.0	-13.5
combined	40.3	-13.2 ± 4.0	-13.6

the combined results. The asymmetries in Table II are obtained from a fit of (12) to the measured angular distribution. The values expected by the GSW theory are listed in the last column.

We will now turn to the interpretation of the measured asymmetry. We rewrite (15) in a somewhat different from to show explicitly the parameters, which determine the asymmetry: the axial vector coupling g_A^e and g_A^μ, the parameter ρ

and the mass of the Z^o boson:

$$A_{\mu\mu} = -\frac{3}{4}\,\frac{\rho G_F}{\sqrt{2}\,\pi\alpha}\,\frac{s\cdot m_Z^2}{m_Z^2-s}\,g_A^e g_A^\mu \qquad (16)$$

We now make different assumptions about these parameters and see what kind of conclusions we can draw from the measurements at PETRA and PEP as listed in Table II.

(1) If we set $\rho = 1$ and $m_Z = 93$ GeV, we find

$$g_A^e \cdot g_A^\mu = 0.27 \pm 0.02 \quad .$$

The ν-e scattering experiments$^{(26)}$ measure $g_A^e = -0.52 \pm 0.06$. Therefore we assume $g_A^e = -1/2$ and determine the axial-vector coupling of the muon

$$g_A^\mu = T_{3L} - T_{3R} = -0.54 \pm 0.04 \quad .$$

The value is in good agreement with the assumption that the left-handed muon is the lower member of a weak iso-doublet and that the right-handed muon is in a weak iso-singlet. Comparing g_A^e with g_A^μ we get an impressive confirmation of the μ-e universality in weak interaction. A similar conclusion can be drawn from the longitudinally polarized muon-carbon experiment$^{(5)}$. Using $\sin^2\theta_W = 0.23$ as an input, the experiment measures

$$T_{3R} = 0.00 \pm 0.06 \pm 0.04 \; .$$

(2) If we believe e-μ universality and the weak isospin assignment of leptons in $SU(2)_L \times U(1)$ we see that the asymmetry allows a determination of

$$\rho \cdot \frac{m_Z^2 \cdot s}{m_Z^2 - s} \quad . \qquad (17)$$

The second term of (17) originates from the Z^o propagator and makes it possible to determine the Z^o-mass. We find with the assumption of $\rho = 1$ that the Z^o mass ranges between 61 GeV and 130 GeV with 95% confidence. This result has however lost impact with the discovery of the Z^o boson by the UA1$^{(27)}$ and UA2$^{(28)}$ experiments and their direct measurement of its mass to be

$m_Z = 95.6 \pm 1.4 \pm 2.9$ GeV UA1

$m_Z = 91.9 \pm 1.3 \pm 1.4$ GeV UA2 .

Thus we take the average value, m_Z = 93 GeV, as an input for (16) and extract a value of the parameter ρ from the measured asymmetries. We find

$$\rho = 1.08 \pm 0.09 \quad .$$

Clearly the error is large, but this value is obtained from purely leptonic reactions. Notice that the CHARM collaboration(29) obtains $\rho = 1.12 \pm 0.12 \pm 0.11$ from ν-e scattering.

Finally, in Fig. 6 we summarize all existing measurements of the muon asymmetry. The low energy points are from PETRA and from SPEAR[30]. We observe an increase of the (negative) asymmetry, which is approximately linear with the c.m. energy squared. At the highest energies measurable deviations from the linear dependence occur due to the Z^o propagator. The highest data points are from very recent data taking at PETRA at energies up to 43 GeV. The errors on these data points will improve within the next year, as PETRA will continue to run at these high energies and will reach 46 GeV.

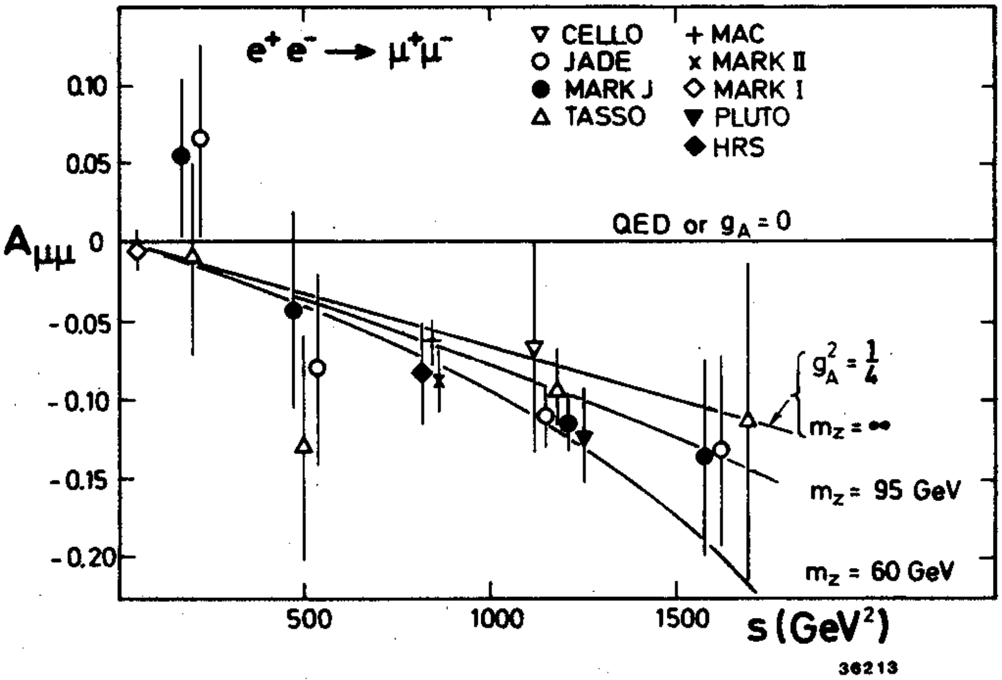


Fig. 6 Measurements of the forward-backward asymmetry of the reaction $e^+e^- \to \mu^+\mu^-$ as a function of the c.m. energy squared. The data are compared to the predictions of an electroweak interference with $g_A^2 = 1/4$ and different masses of the Z^o-boson. Since the measurements are corrected for radiative effects, pure QED or an electroweak theory with $g_A = 0$ predicts no asymmetry.

6.4 COMBINED ANALYSIS OF $e^+e^- \to e^+e^-$ AND $e^+e^- \to \mu^+\mu^-$

The strongest constraints on the vector and axial-vector couplings of leptons can be obtained by combining the measurements of the cross sections and angular distributions of ee → ee and ee → μμ. Fig. 7 displays the 95% C.L. contour in the (g_V, g_A) plane, determined by data from three PETRA experiments, JADE, MARK J and TASSO.

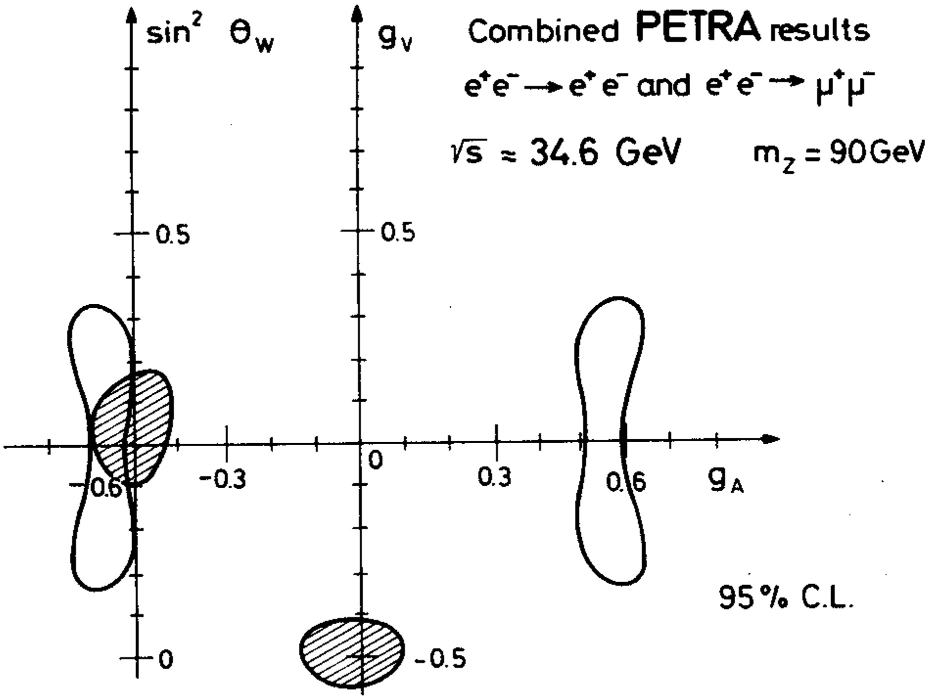


Fig. 7 Allowed regions (95% C.L.) for the vector and axial vector coupling of leptons determined by neutrino electron scattering (shaded area) and by e^+e^- experiments (unshaded regions). The contour for the PETRA experiments is obtained from a combined fit of the reactions $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$. The vector-like solution from νe scattering is clearly excluded, while the axial vector-like solution predicted by the GSW theory for $\sin^2\theta_W = 0.23$ is in good agreement with the measurements of $e^+e^- \to \ell^+\ell^-$.

The allowed region for g_V and g_A has a fourfold symmetry because e^+e^- experiments measure the square of the coupling constants. Neutrino scattering alone limits the values to two regions, a vector-like and a axial-vector-like solution. To resolve this ambiguity one previously had to consider lepton-hadron scattering with the inherent complications of hadronic targets. Now a unique solution can be determined from purely leptonic reactions(31). To reach this conclusion we have assumed the relations $h_{VV} = g_V^2$ and $h_{AA} = g_A^2$. Sakurai has proposed that one compares the ratios h_{VV}/h_{AA} and g_V^2/g_A^2 to exclude one solution(32). In this way we do not make an assumption about the coupling of the Z^0 to neutrinos in the process ν + e → ν + e. From the results shown in Fig. 7 we find

$$\frac{g_V^2}{g_A^2} = \frac{h_{VV}}{h_{AA}} < 0.27 \text{ with 95\% confidence.}$$

This limit excludes the vector-like solution of the neutrino electron scattering data on more general grounds, namely in the framework of models with a single Z^o.

6.5 $e^+e^- \to \tau^+\tau^-$: CROSS SECTION AND SEMILEPTONIC BRANCHING RATIO

The measurement of tau pair production $e^+e^- \to \tau^+\tau^-$ is more complicated because the tau decays after a flight path of less than a few millimeters. However, tau leptons are well recognized by their characteristic decays, either into lepton and neutrinos or into hadrons (low multiplicity) and a neutrino. The statistical and systematic errors of the cross section measurements are generally larger than for $\sigma_{\mu\mu}$ and depend on the fraction of decays which are used to select taus. We refer to the original publications for a detailed description of the selection and the measurement of tau events(16,18-23).

The measurements of $R_{\tau\tau}$, the cross section scaled by the pointlike cross section, are summarized in Fig. 8. The measurements agree well with pure QED

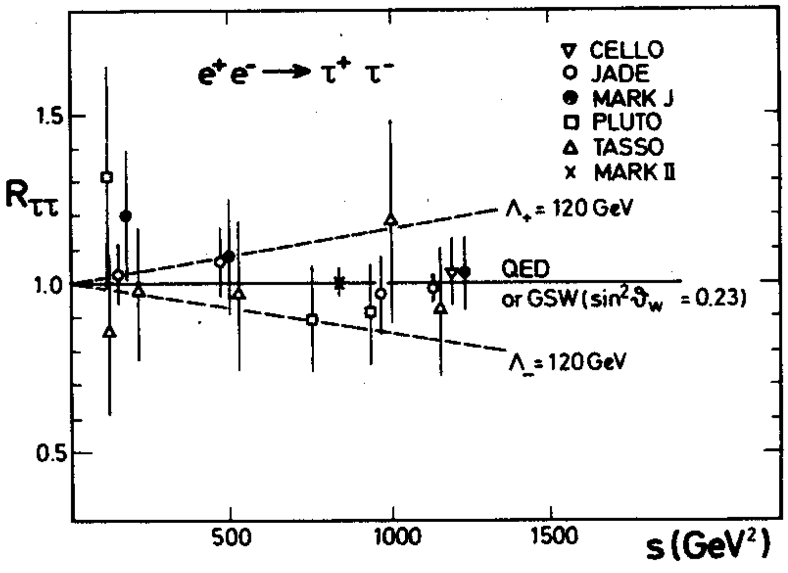


Fig. 8 Measurements of $R_{\tau\tau}$ at different c.m. energies squared. The solid line shows the prediction of pure QED which coincides practically with the prediction of the GSW-theory for $\sin^2\theta_W = 0.23$. Also indicated are the deviations expected if the cut-off parameter $\Lambda_\pm$ would be 120 GeV.

and also with the prediction of GSW for $\sin^2\theta_w = 0.23$. The effect of weak interaction depends on $g_V^e \cdot g_V^\tau$ and since the vector coupling of the electron is close to zero, there is practically no sensitivity to the vector coupling of the tau. We therefore draw the following conclusions from Fig. 8:

1.) The agreement of the cross section with the QED prediction or with the GSW theory with $\sin^2\theta_w \approx 0.23$ allows us to set an upper limit of the cut-off parameter, which is $\Lambda \approx 150$ GeV with 95% confidence level. We conclude that the tau does not show a structure up to an energy scale of 150 GeV and interacts as if pointlike, down to a distance of about 10^{-16} cm. This is especially remarkable in view of the fact that the tau lepton has a mass which is about twice the proton mass.

2.) Alternatively, we assume the validity of QED and determine the branching ratios of tau decay modes which were used for the selection of $ee \to \tau\tau$. Table III shows as an example, the measurements of the leptonic branching ratio for the decay $\tau \to \mu\nu\nu$. We see that the recent measurements have improved the precision of this branching ratio by a factor two.

TABLE III: RESULTS ON THE BRANCHING RATIO FOR $\tau \to \mu\nu\nu$

Experiment	B $(\tau \to \mu\nu\nu)$ in %
CELLO (33)	17.6 ± 2.6 ± 2.1
MAC (22)	17.6 ± 1.5 ± 1.0
MARK-J	17.8 ± 1.6
MARK II (SPEAR) (33)	17.1 ± 0.6 ± 1.0
AVERAGE	17.4 ± 0.8
previous world average	17.5 ± 1.7

6.6 ASYMMETRY OF $e^+e^- \to \tau^+\tau^-$

The angular distribution of tau leptons should show a forward backward asymmetry proportional to $g_A^e \cdot g_A^\tau$, which is completely analogous to that of the reaction $ee \to \mu\mu$. If $g_A^e = g_A^\tau = -1/2$ we expect an asymmetry of -9.4% at 34.5 GeV. This means that negative taus go more frequently in the direction of the positron beam and positive taus tend to follow the electron beam. The charge of the tau lepton is easily determined from the sum of the charges of its decay products. Most of the experiments do not detect all decay modes and have therefore a smaller number of events than in the reaction ee → $\mu\mu$, with attendant larger statistical errors.

Fig. 9 displays the measurements of CELLO, JADE, MARK J and TASSO at PETRA.

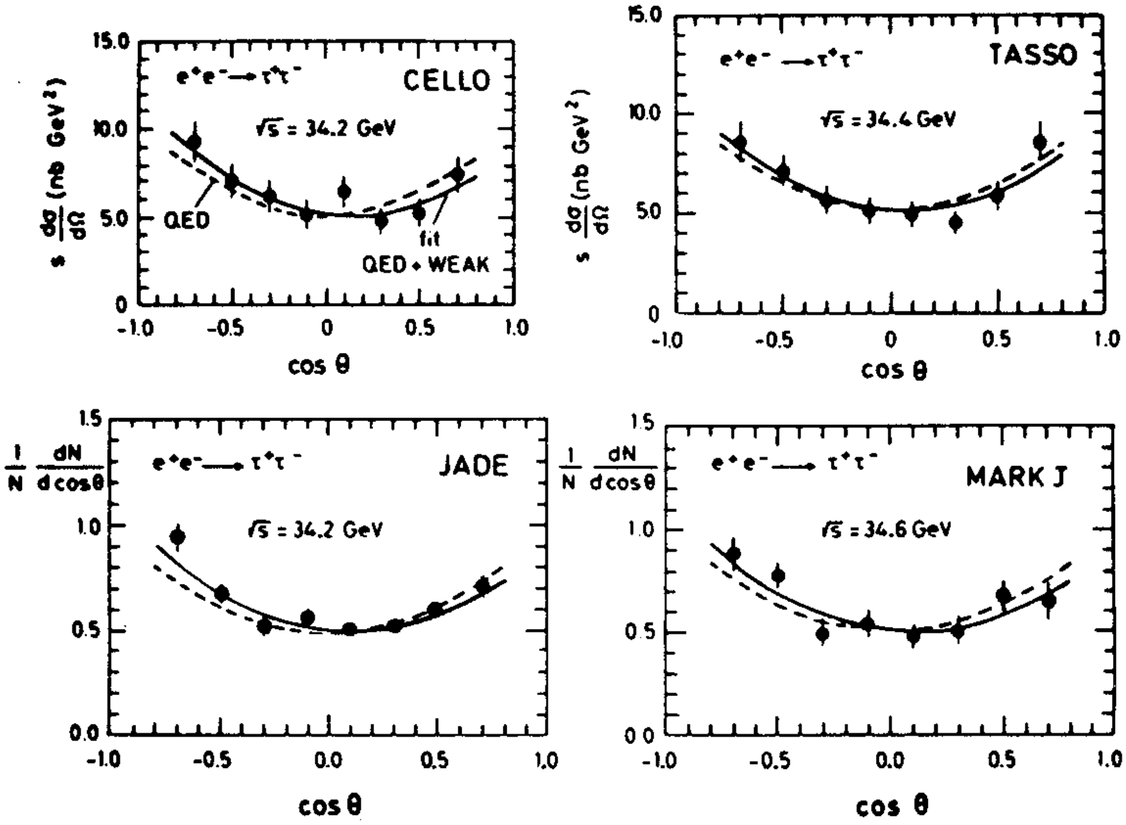


Fig. 9 Angular distribution of $e^+e^- \to \tau^+\tau^-$ measured by CELLO, TASSO, JADE and MARK J at PETRA. The dashed line is the lowest order QED prediction of the form $(1 + \cos^2\theta)$. The solid line is a fit to the data, which includes weak interaction in the form of (12).

The angular distributions are corrected for radiative effects of order α^3 and must therefore be compared with the lowest order QED or electroweak prediction. All four measurements depart from the symmetric $(1+\cos^2\theta)$ distribution predicted by pure QED and prefer a small negative asymmetry. The results on the tau asymmetries from PEP and PETRA are listed in Table IV. The measurements have a systematic error of 1% to 2% in addition to the statistical error. The combined values include the systematic errors. The experiments find a negative asymmetry with a typical significance of about two standard deviations. The combined value from PETRA, dominated by the JADE result, is (-7.6 ± 2.1)%. It is the first significant observation of an electroweak interference associated with the tau. The measured values agree within their errors with the prediction of the GSW theory for $\sin^2\theta_W \approx 0.23$. Since the asymmetry measures the product $g_A^e \cdot g_A^\tau$, we find by

TABLE IV

RESULTS FROM PEP AND PETRA ON THE ASYMMETRY IN THE REACTION $e^+e^- \to \tau^+\tau^-$

Experiment	$\sqrt{s}$ GeV	$A_{\tau\tau}$ in %	Expected in GSW for $\sin^2\theta_w = 0.23$
MAC	29	-1.3 ± 2.9	-6.3
MARK II	29	- 4.5 ± 2.3 ± 0.8	-6.3
PEP Combined	29	- 3.2 ± 1.9	-6.3
CELLO	34.2	-10.3 ± 5.2	-9.2
JADE	34.6	- 7.6 ± 2.7	-9.5
MARK-J	34.6	- 7.8 ± 4.0 ± 2.0	-9.5
TASSO	34.4	- 5.4 ± 4.5	-9.3
PETRA Combined	34.5	- 7.6 ± 2.1	-9.4

combining the PETRA and PEP results (for $m_Z = 93$ GeV)

$$g_A^e \cdot g_A^\tau = 0.18 \pm 0.05 \quad .$$

If we use $g_A^e = -1/2$ we obtain for the axial-vector coupling constant of the tau

$$g_A^\tau = T_{3L} - T_{3R} = -0.36 \pm 0.12 \quad .$$

This value is consistent with the weak isospin assignment of leptons in $SU(2)_L \times U(1)$, i.e. $T_{3L} = -1/2$ and $T_{3R} = 0$. Thus we observe e-μ-τ universality in weak neutral currents.

7. AXIAL-VECTOR COUPLING CONSTANT OF CHARM AND BOTTOM

In analogy to leptons we expect a forward-backward asymmetry of the reaction $e^+e^- \to q\bar{q}$, which depends on the axial-vector coupling of the quark of flavor f and its charge Q_f

$$A = \frac{3}{2} \times \frac{1}{Q_f} g_A^e g_A^f \quad .$$

The factor $\frac{1}{Q_f}$ has the consequence that the asymmetries of quarks are much larger than for leptons. We expect an asymmetry of - 14% for charm quarks and - 25% for bottom quark at 34.5 GeV.(34) A measurement of these asymmetries requires a determination of the quark flavor <u>and</u> the quark charge, i.e. particle-antiparticle separation. Two methods have been employed so far.

In the first method(35) one studies reactions $e^+e^- \rightarrow q\bar{q} \rightarrow \mu$ (or e) + hadrons selecting prompt leptons, which appear to come from the interaction vertex. These events are explained by the semileptonic decay of a heavy quark, more precisely by the decay of a shortlived hadron, which is built up by that quark in the first step of the fragmentation. The sign of the prompt lepton charge indicates the sign of the charge of the parent quark. Examples are $b \rightarrow \mu^- X$ and $c \rightarrow \mu^+ X$. The cascade decay $b \rightarrow c \rightarrow \mu^+ X$ creates some charge confusion but the lepton spectrum is softer and so a cut on the lepton momentum eliminates a large number of these events. Thus we find that positive muons select c-quarks and b-antiquarks; negative muons select c-antiquarks and b-quarks. If we are not able to separate the quark flavors b and c, their asymmetry will partially cancel, because we add particle and antiparticle asymmetries. Therefore a good flavor separation is of major importance for this measurement.

Quark flavors can be selected with variables, which are sensitive to the quark mass. The experimenters use thrust, which measures the width of a jet and the transverse momentum of a prompt lepton with respect to the thrust (jet) axis(36). The observed asymmetries are substantially reduced, because the separation of b and c quarks is incomplete and the event sample contains background from π- and K-decay and punch through.

The second method of flavor tagging selects charged D^* mesons by reconstructing the decay modes $D^{*-} \rightarrow D^o\pi^- \rightarrow K^-\pi^+\pi^-$ and $D^{*-} \rightarrow K^+\pi^-\pi^-$. After a cut on the mass difference between D^* and D^o one observes a D^o peak and uses these events to calculate the asymmetry. This method has a low background, but also a very low number of D^* events, typically about 50 events(37). The hope is that with better mass resolution and with higher acceptance the statistical significance of this measurement will improve in the future.

Table V summarizes the preliminary results for charm and bottom(37,38). The measurements are corrected for acceptance and radiative effects and can be compared to the lowest order electroweak prediction. Although the results, especially for the bottom quark, are not very significant, I made the attempt to combine them. The axial-vector coupling constant of the charm quark is $g_A^c = + 0.77 \pm 0.23$ where we expect $g_A^c = T_{3L} - T_{3R} = + 1/2$ in the $SU(2)_L xU(1)$ theory with $\binom{c}{s},)_L$. For the bottom quark we find $g_A^b = - 0.45 \pm 0.25$, which agrees astonishingly well with $g_A^b = - 1/2$ as expected for $\binom{t}{b},)_L$. Is this an indication that the top quark exists? The answer might be affirmative, since we have further evidence for the existence of the top quark coming from a search for flavor changing neutral currents. If the top quark does not exist

TABLE V

ASYMMETRY AND AXIAL-VECTOR COUPLING OF CHARM AND BOTTOM

Experiment	A_c in %	expected (%)	g_A^c	method
JADE	- 27 ± 14	- 14	+ 1.0 ± 0.5	D*
MARK J	- 17 ± 9	- 14	+ 0.6 ± 0.5	c → μX
TASSO	- 28 ± 13	- 14	+ 1.0 ± 0.5	D*
Experiment	A_b in %	expected (%)	g_A^b	method
MAC	- 7.4 ± 9.2	- 12.2	- 0.3 ± 0.4	b → μX
MARK J	- 15 ± 22	- 25	- 0.3 ± 0.4	b → μX
TASSO	- 17 ± 10	- 8	- 1.1 ± 0.6	b → μX

or if the b-quark is in a weak SU(2) singlet, one expects the branching ratio for $b \rightarrow \mu^+\mu^- X$ to be at least 1% (39). CESR and PETRA experiments study the reaction $e^+e^- \rightarrow b\bar{b}$ and search for a $\mu^+\mu^-$-pair in one of the bottom jets. They find the following upper limits with 95% confidence: (40)

CLEO (CESR)	$B(b \rightarrow \mu^+\mu^- X)$	$< 0.4\%$
JADE and MARK J	$B(b \rightarrow \mu^+\mu^- X)$	$< 0.7\%$.

Thus we conclude that the t-quark is a member of a weak iso-doublet and we have still some hope to find it at PETRA in autum 1983 when we scan up to 46 GeV. Otherwise it will have to be found at the $p\bar{p}$ collider or at new e^+e^- storage rings.

8. ALTERNATIVE MODELS

Alternative models (41) to the standard electroweak theory seem to be strongly restricted since the discovery of the $W^\pm$ and the Z^o. Many composite models or models with a larger gauge group SU(2) x U(1) x G or general electroweak mixing schemes have an effective neutral current lagrangian which in the low q^2 limit (32,42) becomes

$$L_{eff}^{NC} = - \frac{4G_F}{\sqrt{2}} \left[(J_\mu^3 - \sin^2\theta_w \, J_\mu^{em})^2 + C \, (J_\mu^{em})^2 \right] \qquad (18)$$

It differs from SU(2) x U(1) by a term proportional to the square of the electromagnetic current which is parity conserving and which is therefore invisible in the neutrino experiments and in polarized electron-deuteron scattering. However, it modifies the vector coupling and h_{VV}, previously given by (5), becomes

$$h_{VV} = \frac{1}{4}\,(1-4\,\sin^2\theta_w)^2 + 4C \quad . \qquad (19)$$

To reproduce the low energy neutrino and electron-deuteron results we use $\sin^2\theta_w = 0.23$ and determine an upper limit for the parameter C. The results from PETRA listed in Table VI impose strong restrictions to the mass spectrum and coupling of Z^o's in these models.

TABLE VI

UPPER LIMITS TO THE PARAMETER C WITH 95% CONFIDENCE

CELLO (16)	$C < 0.031$	MARK J (43)	$C < 0.025$
JADE (17)	$C < 0.031$	TASSO (20)	$C < 0.011$

9. SUPERSYMMETRY

The search for new particles predicted by supersymmetry has been briefly discussed in chapter 4. Here we consider a model by P. Fayet, who extends the gauge group SU(3) x SU(2) x U(1) by an additional U'(1) to generate large masses to the spin-0 partners of leptons and quarks (13). Experiments on electroweak interference are able to set strong limits on the mass and coupling of the new neutral gauge boson (U-boson) associated with the U'(1). If the U-boson is very light, we expect to see effects in parity violating atomic physics experiments. Fig.10a shows the allowed values for $r^2\cos\phi$ as a function of the U-mass obtained from an analysis of the Cs-experiment at Paris (3,4).

The parameter r^2 is analogous to the ρ parameter and describes the strength of the neutral U current coupling in terms of $G/\sqrt{2}$. The vector part of the left-handed and right-handed U current is parametrized by $(1 \mp \cos\phi)$, respectively. The Cs-experiment restricts these parameters strongly for U-masses between 1 and 1000 MeV.

If the U-boson is heavy, we expect to see a change of the forward-backward asymmetry in the reaction $e^+e^- \to \mu^+\mu^-$ due to the axial coupling of the U-boson and its propagator (13).

$$A_{\mu\mu} = -\frac{3}{4}\,\frac{G\cdot s}{\sqrt{2}\,\pi\alpha}\left[\frac{m_Z^2}{m_Z^2 - s} + r^2\,\frac{m_U^2}{m_U^2 - s}\right] \quad . \qquad (20)$$

Since the asymmetries measured at PETRA and PEP (chapter 6.2) are close to the prediction of the standard model, we are able to limit the range of the parameter r^2 and the mass of the U-boson severely. An example determined

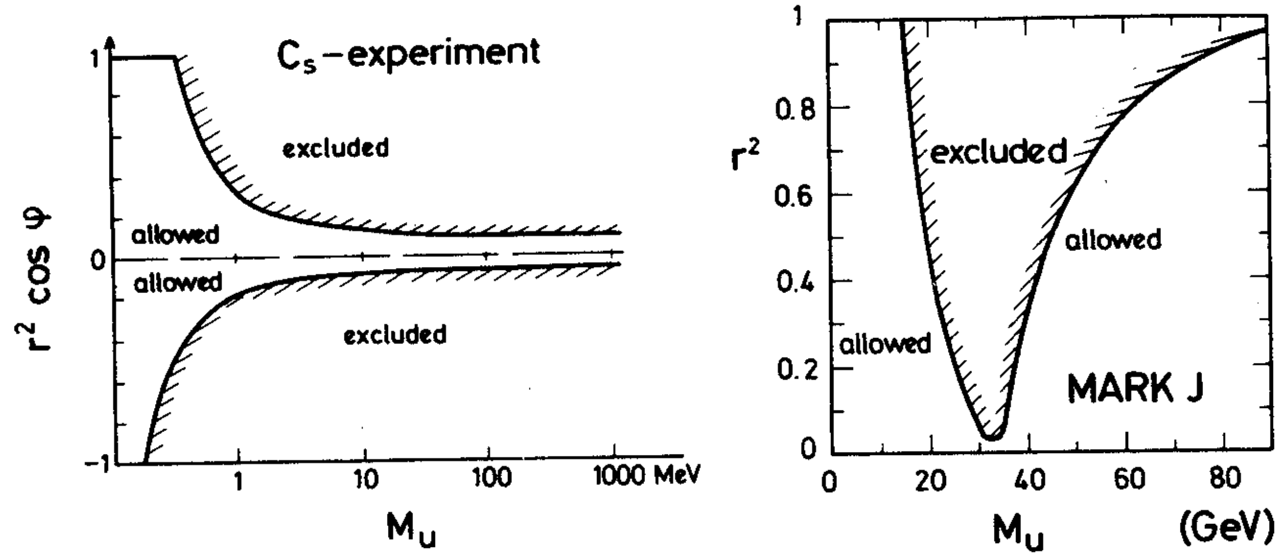


Fig.10 Limits (95% C.L.) to the coupling parameters $r^2\cos\phi$ and r^2 of a supersymmetric theory with a gauge group SU(3) x SU(2) x U(1) x U'(1) evaluated from the Cs-experiment$^{(4)}$ and the MARK-J experiment$^{(43)}$ for different masses of the U-boson.

from the asymmetry measured by MARK J is also shown in Fig.10 $^{(43)}$.

CONCLUSIONS

1. Experiments on electroweak interference test the electroweak theory over a wide range of q^2 and s between a few MeV^2 and $1600 \cdot GeV^2$.
2. A large amount of information has been obtained from e^+e^- experiments.
3. No new lepton, nor quark, nor fundamental scalar or pseudoscalar particles have been observed.
4. Leptons, including the tau, and quarks interact as if pointlike down to a distance of 10^{-16} cm.
5. The asymmetries due to the axial-vector coupling of the muon and tau have been unambiguously observed.
6. The neutral current couplings of leptons agree within errors with the standard model and we observed e-μ-τ universality of weak neutral currents.
7. The study of neutral current couplings of heavy quarks in $e^+e^- \to$ hadrons is more difficult. First progress has been made indicating $T_{3L}(c) = + 1/2$ and $T_{3L}(b) = - 1/2$.

8. Furthermore, since we do not observe flavor changing decays b → $\mu^+\mu^-X$, we are confident that the top quark exists. So lets find it!

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