ELECTROWEAK TESTS

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ABSTRACT

I will report on measurements of the electroweak interactions of leptons and quarks in high energy electron positron collisions concentrating on new data from PETRA which is not reported elsewhere at this conference. The purely leptonic interactions, Bhabha scattering, muon pair production and tau pair production have been studied in detail and the experiments at PETRA have observed weak neutral current effects for the first time in the measurement of the forward backward charge asymmetry in muon pair production at q^2's of around 1200 GeV^2. The data are interpreted in terms of values of $\sin^2\theta_W$ in the standard model and of g_A, g_V, and C in more general models of electroweak interactions. Using measurements of R, we make a more accurate determination of $\sin^2\theta_W$ at high q^2. The semileptonic branching ratio of B particle decay is measured as a preview of possible determination of the asymmetry in b and c quark production at high q^2. Finally, we look for structure in the fermions, e, μ, τ, and q by the study of their high q^2 interactions.

I. INTRODUCTION

The standard theory of electroweak interactions[1], based on broken SU(2) x U(1) symmetry has been very successful in fitting all of the presently available data. Indeed this theory even predicted many of the features of the data. It predicted the existence of a $\Delta S = 0$ neutral current, even though $\Delta S \neq 0$ currents were limited by experiment to be very small. Since the weak neutral current was discovered[2] in neutrino scattering, very detailed measurements[3] have been made of its structure, particularly by scattering neutrinos off quarks. All of the data from these experiments can be fit by the original theory with its one free parameter, $\sin^2\theta_W$, which determines the mixing between the original weak and electromagnetic currents caused by symmetry breaking. Data from the purely leptonic neutrino electron[4] scattering also are fit by the theory with the same value of $\sin^2\theta_W$. Finally, a very high accuracy measurement[5] of parity violation in electron deuteron scattering also was in agreement with the theory and determined the SU(2) multiplet structure of the fermions to be as originally expected.

The theory has therefore been tested very stringently by the combination of all of these experiments. However, many of the most interesting features of the theory, such as spontaneous symmetry breaking and the existence of the intermediate vector bosons, are not yet required by the data. As was first pointed out by Bjorken[6], all that is needed to fit the data is a global SU(2) symmetry, with electromagnetic mixing and universality. The new tests needed to pin down these principles of the theory are to find the scalar particles that cause the spontaneous symmetry breaking and to make measurements at high q^2 where boson structure of the interaction may be determined.

To be more specific, several authors[7] have proposed alterations to the standard theory which would give a different boson structure. The least radical change among these has first been proposed by Georgi and Weinberg. They showed that by extending the symmetry group from SU(2) x U(1) to SU(2) x U(1) x G, all of the low energy predictions of the model remain unchanged. At high energy, however, the extended models have a richer boson structure. A more radical example of a model is one where the W's and the Z's are composed of constituents and at energies above the mass of the W and Z resonances, a continuum of weak interactions occur in a spectrum in some ways similar to quarkonium followed by continuum production of new flavors.

At low energy, all of the models, including the standard theory, can be described by an effective neutral current Hamiltonian

$$2H_{NC} = \frac{-e^2}{q^2}\, j^2_{EM} + \frac{8G_F}{\sqrt{2}} \left| (j^{(3)} - \sin^2\theta_W j_{EM})^2 + C\, j^2_{EM} \right| \tag{1}$$

where $j^{(3)}$ is the third component of the weak isospin current.

$$\vec{j}_\mu = \sum_i \bar{\psi}\, \gamma_\mu \left(\frac{1-\gamma_5}{2} \right) \frac{\vec{\tau}}{2}\, \psi_i \tag{2}$$

with the sum running over all weak fermion doublets. In the standard theory, as in any theory with a single Z boson, the constant C is equal to zero. In theories with more than one Z boson, C will be greater than zero.

Gounaris and Schildknecht[8] have given a nice interpretation of the parameter C in terms of a deviation from the standard model. They found

$$16\ C = \frac{\left| \int \frac{ds}{s}\, \sigma(e^+e^- \to \text{ALL}) \right|_{\text{TRUE THEORY}} - \left| \int \frac{ds}{s}\, \sigma(e^+e^- \to \text{ALL}) \right|_{\text{STANDARD THEORY}}}{\left| \int \frac{ds}{s}\, \sigma(e^+e^- \to \text{ALL}) \right|_{\text{STANDARD THEORY}}} \tag{3}$$

so that the quantity 16 C measures the deviation of the total e^+e^- cross section from the standard theory, integrated over all energy with the weighting factor 1/s. C will therefore be a parameter of general interest to weak interaction model builders.

Throughout the paper, I will describe the strength of the axial vector and vector couplings of the weak neutral current in terms of the dimensionless coupling constants g_A and g_V. In the standard model we have for the left handed fermion doublets under weak SU(2)

$$g_A = T_3$$
$$g_V = T_3 - 2\sin^2\theta_W \tag{4}$$

In the Hamiltonian of equation (1), the axial vector-axial vector term is proportional to g_A^2, the axial vector-vector term is proportional to $g_A g_V$, and the vector-vector term is proportional to $(g_V^2 + 4C)$.

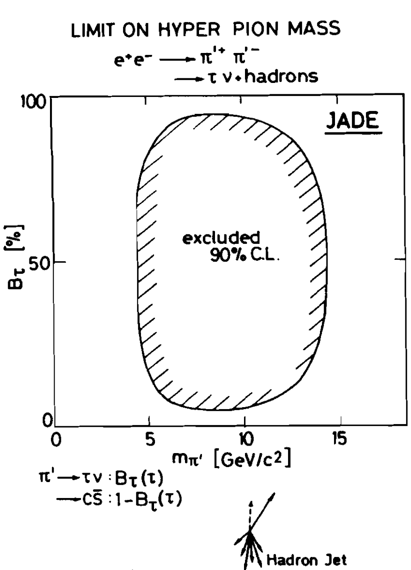


Fig. 1

Of course an important aspect of the present weak interaction theory is spontaneous symmetry breaking by the Higgs mechanism. The standard theory predicts that there should be an observable neutral scalar particle. As yet, no such particle has been found nor have any stringent limits been placed on its mass. This may become possible if the top threshold is reached and the Higgs particle can be searched for in production by the Wilcek mechanism[9]. However, technicolor[10] models, which have dynamical symmetry breaking, predict the existence of reasonably light charged particles, known as technipions, which will be produced in pairs in e^+e^-. One search for a technipion, alias hyperpion, is shown in Fig. 1. At the 90% confidence level, the technipion is excluded in the mass range between 5 and 14 GeV for most decay scenarios, i.e. a mixture between $\tau\bar{\nu}$ decays and $c\,\bar{s}$ decays. Charged Higgs particles, which are not required by the standard model but may exist, have similar properties and are also excluded in this mass range.

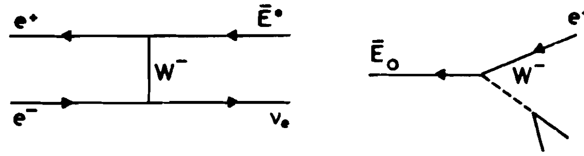
Additional leptons of various types have been searched for at PETRA. New sequential leptons have been excluded with mass limits shown in Table I by the experiments. These limits will only improve as the center of mass energy is increased.

TABLE I

95% C.L. LOWER MASS LIMIT ON SEQUENCIAL HEAVY LEPTONS

JADE	18.1
MARK-J	16.0
PLUTO	14.5
TASSO	15.5

JADE has searched for a neutral heavy electron, which although it is only produced weakly, has a very distinctive signature of a jet containing an electron recoiling against only an unobserved neutrino.



They find that $3 < M_{E_o} < 20$ GeV V + A

$3 < M_{E_o} < 17$ GeV V − A .

So no new families of fermions have been found and no unusual leptons that do not fit into the standard SU(2) scheme have been found either.

II. ELECTROWEAK INTERACTIONS OF THE CHARGED LEPTONS

The reactions

$e^+e^- \to e^+e^-$ (Bhabha Scattering)

$e^+e^- \to \mu^+\mu^-$ (Muon Pair Production)

$e^+e^- \to \tau^+\tau^-$ (Tau Pair Production)

have been studied at PETRA in terms of electroweak models. Much of the data which I present here has not yet been published by the experimental groups and should therefore be considered preliminary. The same types of analysis of smaller data samples have been published[11].

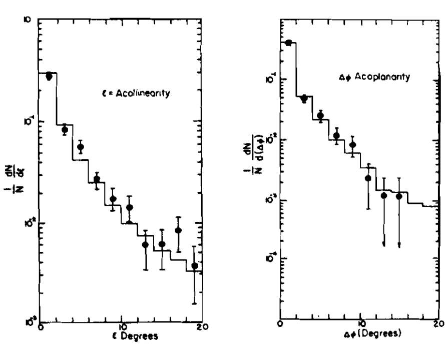


Fig. 2

For all of the measured processes, order α^3 QED calculations are necessary to test weak interaction effects because the order α^3 radiative corrections are generally about the same size as the weak effects. These calculations have been made by Berends, Gaemers, Gastmans and Kleiss[12]. Monte Carlo event generators with the order α^3 matrix elements have been supplied to us by Berends and Kleiss. With these generators we are able to pass the events through our detector simulation and analysis programs so that the effects of resolution and experimental cuts on the radiative corrections can be accurately represented. Of particular note is the inclusion of hadronic vacuum polarization effects in a form slightly modified from that originally published by Berends and Komen[13]. Some effects of radiation of photons can be measured as a partial check of the calculations. Figures 2 and 3 show some of these measurements. In Fig. 2, the measured acollinearity and acoplanarity distributions for muon pair production are compared to the expectation from Monte Carlo. Good agreement is found. Similarly, the acollinearity distribution for Bhabha scattering shown in Fig. 3

agrees well with expectation.

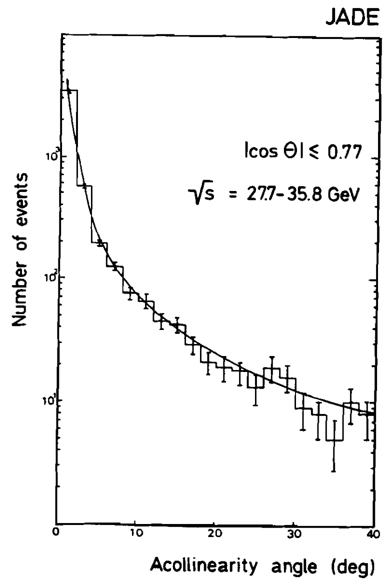


Fig. 3

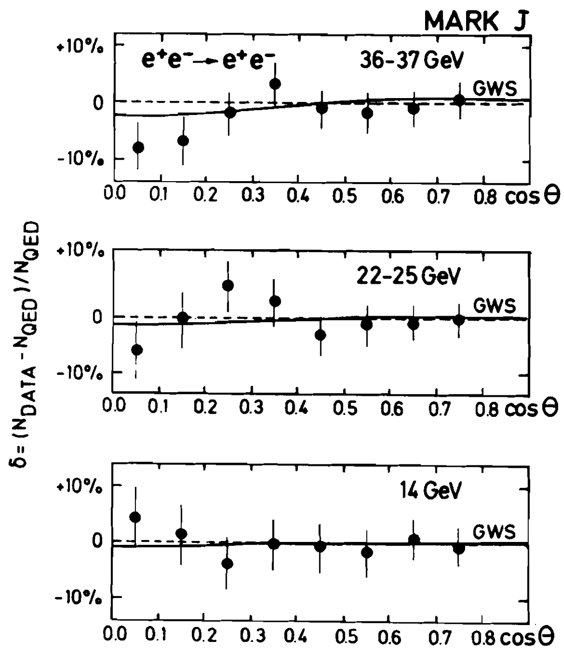


Fig. 5

Bhabha Scattering

The data from Bhabha scattering that are of relevance to our tests of the electroweak interaction are the angular distributions of the final state electron and positron. In the absence of beam polarization(14), the distribution is symmetric in the azimuthal angle ϕ, but has a very strong dependence in the polar angle from the beam axis, θ.

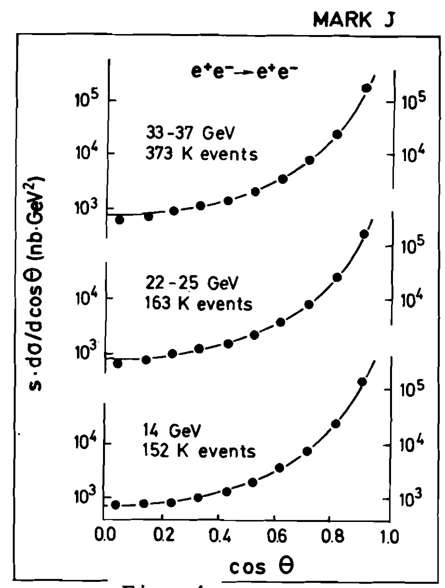


Fig. 4

Fig. 4 is a graph of s $\frac{d\sigma}{d\cos\theta}$ for 3 center of mass energies. Data, with error bars invisible on this scale, are compared with the Monte Carlo calculation of order α^3 QED. As the cross section is steeply falling, it is difficult to see the details of the match between measurement and theory. A more clear exposition of this may be obtained by plotting the fractional difference between data and theory.

$$\delta = \frac{N_{DATA} - N_{QED}}{N_{QED}} \qquad (5)$$

In Fig. 5, the distributions from Fig. 4 are shown again as a graph of δ vs. cos θ. If the data agreed exactly with QED, the points should lie on the horizontal line at 0. The solid line drawn in the figure is the expectation for the standard theory of Glashow, Weinberg and Salam, with $\sin^2\theta_W = 0.23$. One can see in the plots of the data at lower energies that the expected difference between QED and GWS is smaller than at high energy. The data at high energy favor GWS over pure QED but are not conclusive. A 3% systematic point to point error is included in the error bars. At lower energies the data are equally compatible with QED or QED plus weak interactions.

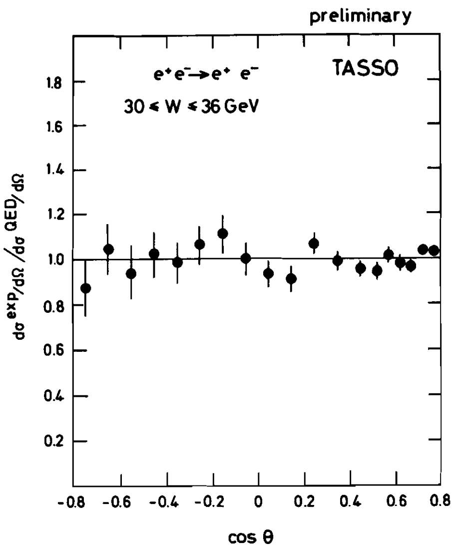


Fig. 6

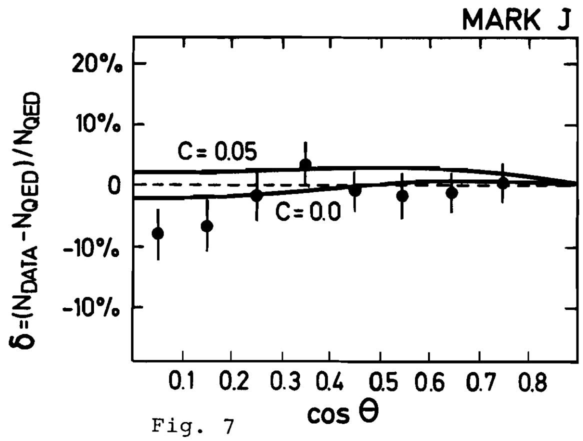


Fig. 7

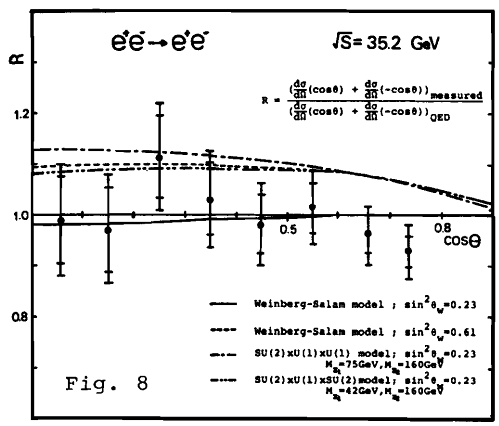


Fig. 8

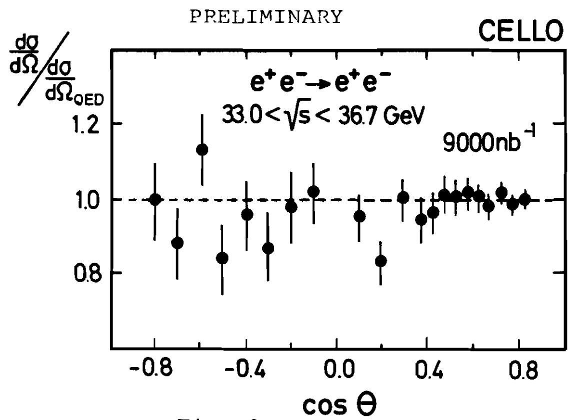


Fig. 9

Although the weak effects expected in the standard model are small, they may be much larger if we use other possible models. For example, Fig. 6 shows the TASSO data compared to the standard model with different values of $\sin^2\theta_W$. As you can see from the figure, the minimum effect is near the measured value of $\sin^2\theta_W$. Fig. 7 compares the MARK-J data to models with different values of C. C = 0 fits the data well, while C = 0.5 is obviously excluded because the line lies above almost all points. In Fig. 8, δ from the JADE experiment is compared to electroweak models with multiple Z bosons. Finally, in Fig. 9, the data from CELLO is shown.

Muon Pair Production

In muon pair production, the total cross section and the polar angular distribution are sensitive to weak effects. The weak effect is expected to be small for the total cross section in the case of the standard model. However, like the results for Bhabha scattering, if one goes outside the standard model, the effects on the total cross section may be quite large. On the other hand, the weak effect in the angular distribution, and in particular, in the forward-backward charge asymmetry, is of measurable size in the standard model and generally larger in other models. We will, therefore, look at both the total cross section and the forward-backward asymmetry, but will not be too surprised if it is the charge asymmetry where we can observe weak effects.

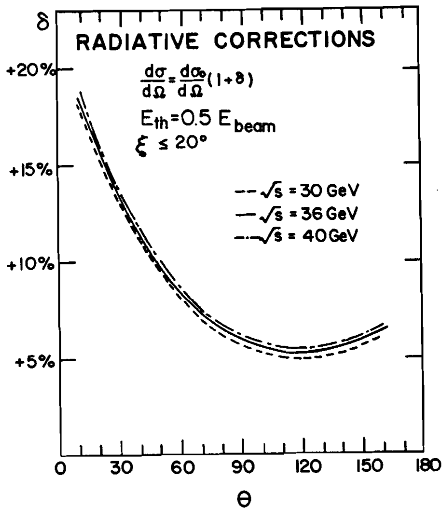


Fig. 10

The radiative correction to $d\sigma/d\Omega$ for muon pair production are shown in Fig. 10 as a function of the polar angle θ. This correction is for the particular cuts on muon pair events that each muon have at least 50% of a beam energy and that the two muons be collinear within 20°. The correction is not symmetric about 90°, indicating that there is a pure QED forward-backward charge asymmetry, which must be corrected for, to measure weak effects. I will discuss this correction again when I come to the charge asymmetry.

The data on the total muon pair production cross section are summarized in Fig. 11. Results from all five PETRA experiments are shown as a function of $\sqrt{s}$. The data have been corrected for radiative effects and are, therefore, compared to the simple prediction of lowest order QED. Neither large disagreements nor unusual structure are found.

The angular distributions from the individual experiments and if one looks carefully, one may begin to see a forward-backward asymmetry that I will quantify shortly.

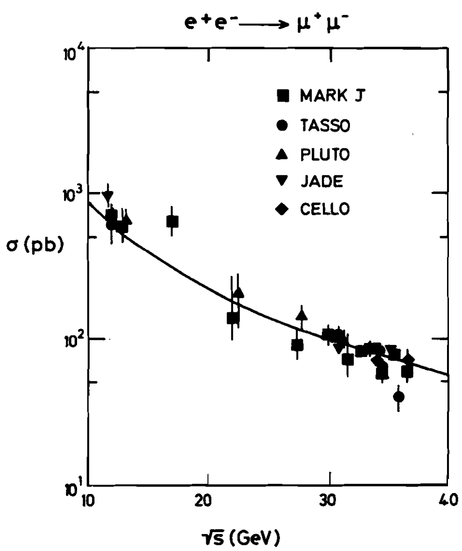


Fig. 11

PRELIMINARY

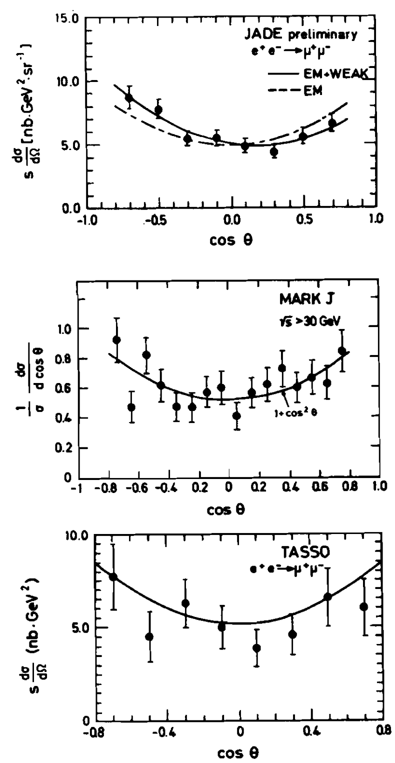


Fig. 12

Tau Pair Production

Fig. 13 is similar to Fig. 11 but the tau pair production cross section is plotted rather than that for muons. Again, no unusual structure is seen. In Fig. 14, the tau pair angular distribution from the CELLO group is shown. Besides these standard measurements for tau, the lifetime can also be measured. This gives information about its charged current coupling constant. TASSO has made a determination of the τ lifetime by measuring the distance taus travel before they decay. A distribution of the measured decay time for taus is shown in Fig. 15. By looking at the centroid of this distribution,whose width is dominated by resolution, the lifetime can be determined.

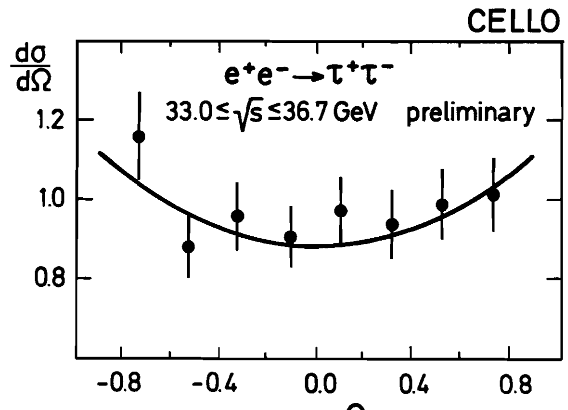


Fig. 13

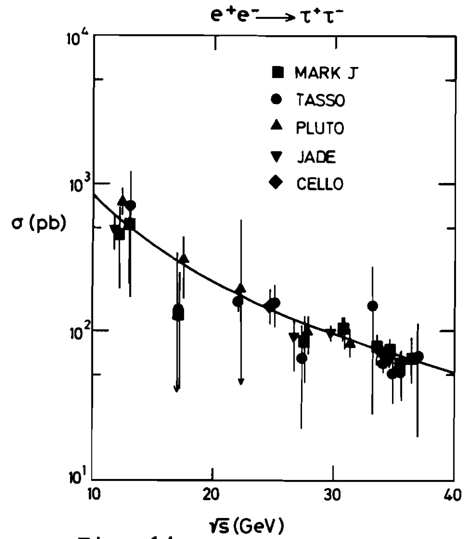


Fig. 14

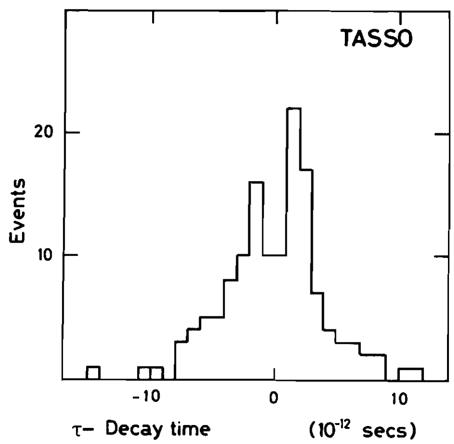


Fig. 15

They find

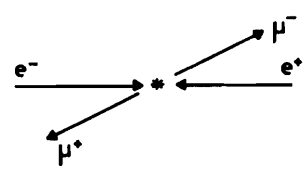
$$<\tau_\tau> = (-0.25\pm3.5)\times 10^{-13}\text{sec}$$

If the tau couples to the weak charged current with the same strength as the electron, then one expects a lifetime of 3×10^{-13} seconds. This is consistent with the measurement and from this they can say that, at the 95% confidence level, $g_\tau > 0.73\ g_e$. At this conference MARK II[14] has also reported a measurement of

$$\tau_\tau = (4.9\pm1.8)\times 10^{-13}\text{seconds}.$$

Charge Asymmetry

The final item of data on the electroweak interaction of the charged leptons is the forward-backward charge asymmetry in the production of muon pairs and of tau pairs. The polar angle θ is defined as the angle between the initital electron direction and the final μ^- or τ^- direction.



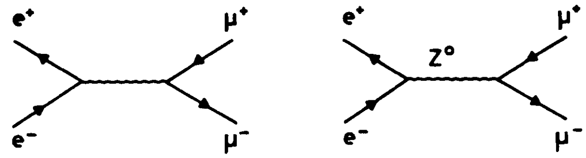
The forward hemisphere is then defined as $0^{\circ} < \theta < 90^{\circ}$ and the backward hemisphere as $90^{\circ} < \theta < 180^{\circ}$. The asymmetry as a function of θ is defined to be

$$A_{\mu\mu}(\theta) = \frac{N_{\mu^-}(\theta) - N_{\mu^-}(\pi-\theta)}{N_{\mu^-}(\theta) + N_{\mu^-}(\pi-\theta)} \qquad (6)$$

Since statistics are still low, the number usually quoted is integrated over angle

$$A_{\mu\mu} = \frac{N_{\mathrm{FORWARD}} - N_{\mathrm{BACKWARD}}}{N_{\mathrm{FORWARD}} + N_{\mathrm{BACKWARD}}} \qquad (7)$$

We can compute the asymmetry in lowest order using just the two diagrams



Using this lowest order computation, the differential muon pair cross section is

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s} \left| F_1(1+\cos^2\theta) + F_2\cos\theta \right| \qquad (8)$$

where

$$F_1 = 1 + 8sgg_V^2 \left(\frac{M_Z^2}{s-M_Z^2} \right) + 16s^2g^2(g_V^2 + g_A^2)^2 \left(\frac{M_Z^2}{s-M_Z^2} \right)^2$$

$$F_2 = 16\, sgg_A^2 \left(\frac{M_Z^2}{s-M_Z^2} \right) + 128s^2g^2g_V^2g_A^2 \left(\frac{M_Z^2}{s-M_Z^2} \right)^2$$

$$g = \frac{G_F}{8\sqrt{s}\,\pi\alpha} = 4.49 \times 10^{-5}\ \mathrm{GeV}^{-2}$$

and g_A and g_V are the previously defined axial vector and vector coupling constants for the charged leptons. The asymmetry piece of the cross section is the part proportional to $\cos\theta$. By putting in some numbers one can see that at PETRA energies F_2 is small compared to F_1 and that, in both F_1 and F_2, the first terms dominate. The first term in F_1 is the purely electromagnetic term and the first term in F_2 is due to weak electromagnetic interference. We may then write down an approximate formula for the asymmetry to investigate its dependence on the lepton coupling constants, the center of mass energy and the polar angle

$$A_{\mu\mu} \approx 7\times10^{-4}s\, g_A^2 \left(\frac{M_Z^2}{s-M_Z^2}\right) \frac{\cos\theta}{1+\cos^2\theta} \qquad (9)$$

This formula is graphed in Fig. 16.

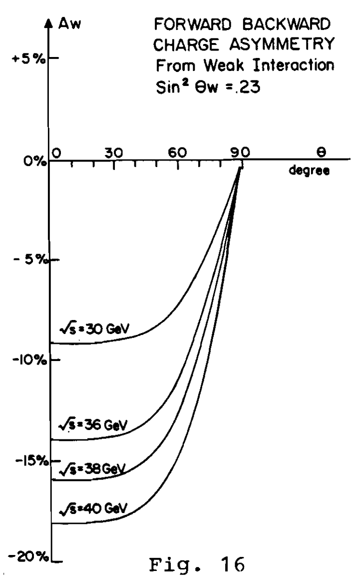


Fig. 16

The asymmetry in this approximation depends only on the axial vector coupling of the electron and muon. It grows as the center of mass energy squared for $s \ll M_Z^2$ and is negative in this region. As a approaches M_Z^2 the pure weak terms of course must also be included. Since the effect grows sharply with $\sqrt{s}$, it is important to make measurements at as high an energy as possible. From the figure we can see that by running at 40 GeV, we get nearly twice the asymmetry as running at 30 GeV. Finally, the simple angular dependence of the asymmetry is plotted in the figure and it should be noted that the maximum effect is at small angle to the beam. So it is important to measure over a large acceptance to get the maximum effect.

Of course to do the calculation properly, we must look at order α^3 effects from QED. These are included in the Monte Carlo generator and the QED asymmetry due to them is shown in Fig. 17. This asymmetry is somewhat smaller than that we expect from weak effects, but is of opposite sign. It gets large as $\theta \to 0$ but the experiments do not measure for $|\cos\theta| > 0.8$ so that the maximum effect is around 3% and the angular averaged effect is about 1.5%. This indicates that higher order QED effects may be neglected.

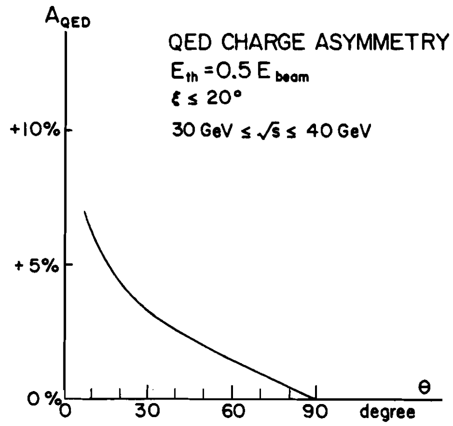


Fig.17

The charge asymmetry in muon pair production has been measured by all five experiments at PETRA and I had received preliminary results up to the time of the conference from JADE, MARK-J, PLUTO, and TASSO. All of these groups estimate that their systematic error in determining the charge asymmetry is very small, that is, 0% to 2%. In most cases this has been tested by looking at the asymmetry in high momentum cosmic rays. The measured asymmetries are given in Table II. Values for the tau pair asymmetry are also given but are obviously of less statistical relevance.

The values from the different groups are computed in slightly different ways. TASSO, for example, quotes the fit value of the asymmetry for 100% acceptance. The other experiments quote a number that is integrated over their acceptance. The average center of mass energy is around 33 GeV,with PLUTO's average slightly lower than the rest because their detector has been moved out during the recent higher energy running.

TABLE II

	JADE	MARK-J	PLUTO	TASSO	COMBINED
$A_{\mu\mu}$	-11±4%	-3±4%	+7±10%	-11.3±5.0%	-7.7±2.4%
EXPECTED	-7.8%	-7.1%	-5.8%	-8.7%	-7.8%
$A_{\tau\tau}$		-6±12		0±11	
EXPECTED		-5		-7	

The averaged value is of particular interest. Since the systematic errors are small, compared even to the combined statistical error, averaging greatly improves the precision of the measurement. The average has been made, taking into account the fact that a higher expected asymmetry improves the ability to measure weak effects. This was done by normalizing experimental values and errors to the expected asymmetry, then making the weighted average between experiments and finally, converting back to an average asymmetry. The expected value corresponds merely to the unnormalized expected values averaged with the same weights. The four data points give a χ^2 of 3.6 for three degrees of freedom.

The result, as shown in the table, is $A_{\mu\mu} = -7.7\% \pm 2.4\%$ expecting -7.8% in the standard model. Thus weak effects have been observed for the first time at PETRA in this three standard deviation effect. This is also the highest q^2 at which weak effects have been measured, the average q^2 being around 1200 GeV^2.

From the measurement, we can determine the axial vector coupling constant for the charged leptons assuming only universality and that we are far from Z^0 pole(s)

$$|g_A| = 0.50 \begin{smallmatrix}+0.07\\-0.09\end{smallmatrix}$$

or at the 95% confidence level,

$$0.31 < |g_A| < 0.63.$$

The effect of the propagator, $M_Z^2/(s-M_Z^2)$, cannot yet be measured except in terms of a lower limit on the Z^0 mass which is independent of the standard model but assumes that a single Z^0 is responsible for e-D parity violation and $A_{\mu\mu}$. We find at the 95% confidence level

$$M_Z > 50 \text{ GeV}.$$

CELLO, MAC[15], and MARK II have reported asymmetry results at this conference which I was not able to include in my analysis. These are:

CELLO	$-1.3\% \begin{smallmatrix}+8\%\\-10\%\end{smallmatrix}$	expecting -5.8%
MAC	$-0.9\% \pm 5.7\%$	expecting -5.0%
MARK II	$-4.0\% \pm 3.5\%$	expecting -5.0%.

Interpretation of Leptonic Data

The simplest interpretation of the data is a measurement of $\sin^2\theta_W$ in the standard model. Table III gives the results from the five PETRA experiments for $\sin^2\theta_W$ determined from purely leptonic processes.

TABLE III

$\sin^2\theta_W$ FROM PURELY LEPTONIC REACTIONS

	$\sin^2\theta_W$	Leptons Used
CELLO	$0.22^{+0.15}_{-0.10}$	e^+e^-, $\tau^+\tau^-$, $A_{\tau\tau}$
JADE	0.25 ± 0.15	e^+e^-, $\mu^+\mu^-$, $A_{\mu\mu}$
MARK-J	0.25 ± 0.11	e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $A_{\mu\mu}$
PLUTO	0.23 ± 0.17	e^+e^-, $\mu^+\mu^-$
TASSO	0.25 ± 0.10	e^+e^-, $\mu^+\mu^-$, $A_{\mu\mu}$

The value of 0.25 for $\sin^2\theta_W$ is a very likely one because this type of experiment is sensitive to g_A^2 and to g_V^2. If the effect of g_V^2 is measured to be less than zero, then the best that can be done within the standard model is to make $g_V^2 = 0$, in which case $\sin^2\theta_W = 0.25$. Since g_V is indeed expected to be very small compared to the accuracy with which it is measured here, the experiments have nearly a 50% chance of measuring $\sin^2\theta_W = 0.25$.

It should be pointed out again that no disagreement with the standard model has been found. So our result, in terms of the standard model, is that $\sin^2\theta_W \approx 0.25\pm0.10$.

Outside the standard theory, we may determine g_A and g_V for charged leptons. This will also show quantitatively whether the data are in agreement with the standard theory. Fig. 18 shows the measured value of g_A^2 versus the measured value of g_V^2 for the five PETRA experiments with error bars denoting the one sigma error. The points cluster together quite well in a region near $g_V^2 \approx 0.0$ and $g_A^2 \approx 0.2$. The data presented by MARK II[15] are consistent with these results. Many of the experiments measure $g_V^2 < 0$, but within the statistical error quite consistent with zero. This gives the value of $\sin^2\theta_W = 0.25$ in the previous **table.** Note, however, that because M_Z^2 depends on $\sin^2\theta_W$ in the standard theory,

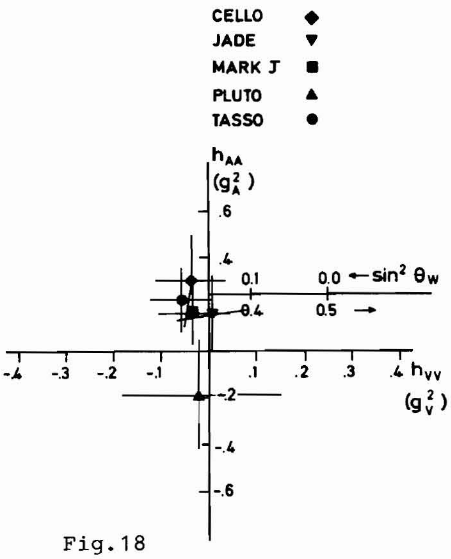


Fig. 18

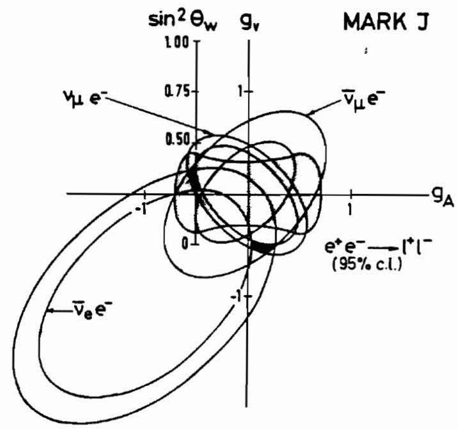


Fig. 19

values other than $\sin^2\theta_W = 0.25$ can give the best fit, even if g_V^2 is $\leq$ 0, due primarily to propagator effects in the asymmetry. The prediction of the standard theory is also displayed in Fig. 18 as a function of $\sin^2\theta_W$. Because we look at g_V^2, the prediction is symmetric about $\sin^2\theta_W = 0.25$ which explains the double labelling of the axis. For $\sin^2\theta_W = 0.25$, g_V^2 is zero. The model predicts $g_A^2 = 0.25$ independent of $\sin^2\theta_W$. Most of the data points are within one sigma of the standard model with $\sin^2\theta_W = 0.23$ as measured in neutrino scattering from hadrons.

Alternatively, we may compare and combine our results with those of another purely leptonic process, neutrino electron scattering. In Fig. 19, the results of determination of g_A and g_V for the charged leptons are shown for ν_e scattering and for the MARK-J data from PETRA. The ν_e scattering 68% confidence level limits are the three elliptical regions. By combining three different kinds of experiments, the coupling constants can be limited to two regions in the plane. These are the dark regions in the figure at the overlap of all three elliptical regions. We can discriminate between the two regions by using the data from MARK-J. The shaded area centered at the origin is the 95% confidence level contour from the e^+e^- data. This area is symmetric about the lines $g_A = 0$ and $g_V = 0$ because only g_A^2 and g_V^2 have any significant effect on the e^+e^- data. These data nicely eliminate one of the two solutions, leaving only the one near $g_A = 0.5$ and $g_V = 0.2$. So combining all of the data, one can limit g_A and g_V to be in a small region which again is quite consistent with the standard theory shown by the line.

ELECTROWEAK INTERACTION AT PETRA

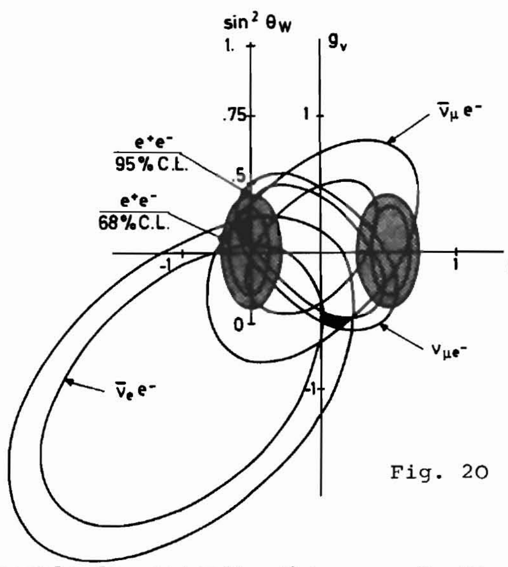


Fig. 20

If we use the MARK-J data on Bhabha scattering and total muon pair production in conunction with the combined PETRA value of the asymmetry, the e^+e^- result dramatically changes. In Fig. 20, we show the same thing as in Fig. 19 but now using the combined asymmetry. The 95% confidence level region from e^+e^- remains symmetric about g = 0 and $g_V = 0$, but it has now separated into two disjoint areas. This is if course because g_A is 0 is ruled out at greater than the 95% confidence level by the asymmetry measurement which is three standard deviations from zero. The left hand region is still consistent with the standard theory and with one of the ν_e scattering regions. One can see that the e^+e^- purely leptonic data are approaching similar significance as the combined ν_e scattering data. These data, however, are from different q^2 regions, the ν_e data coming from very low q^2 and the e^+e^- data from $q^2 \approx (0\text{-}15)M_Z^2$.

In the introduction I defined the parameter C, which is the coefficient of a term in the weak neutral current Hamiltonian proportional to the electromagnetic current squared. This kind of term is expected in multiboson weak models and also in more radical models where there is a continuum of weak interactions perhaps due to a constituent nature of the weak bosons. With multiple bosons, the model can no longer be parameterized in terms of g_A and g_V only. C is expected to be greater or equal to zero in all models.

Limits on C, which are applicable to any model of the weak neutral current, have been obtained by all of the PETRA experiments and are shown in Table IV. All the results are consistent with C = 0.

TABLE IV

LIMITS ON PARAMETER C

	95% Confidence Limit on C
CELLO	< 0.032
JADE	< 0.039
MARK-J	< 0.027
PLUTO	< 0.060
TASSO	< 0.030

If we take the tightest of these limits, we may put a limit on the normalized difference between the actual theory and the standard theory, which is equal to 16 C. More specifically

$$\frac{\left|\int \frac{ds}{s}\,\sigma(e^+e^- \to \text{ALL})\right|_{\substack{\text{ACTUAL}\\\text{THEORY}}} - \left|\int \frac{ds}{s}\,\sigma(e^+e^- \to \text{ALL})\right|_{\substack{\text{STANDARD}\\\text{THEORY}}}}{\left|\int \frac{ds}{s}\,\sigma(e^+e^- \to \text{ALL})\right|_{\text{STANDARD THEORY}}} < 0.43$$

at the 95% confidence level. Therefore, in terms of this weighted integral over all energy, we have determined that the actual theory of weak interactions is within 50% of the standard model. Of course improved accuracy is desired.

As examples, we have looked at two specific[7] models of simple extensions of the standard model. These are

$$SU(2) \times U(1) \times U(1)$$
$$\text{and} \quad SU(2) \times U(1) \times SU(2).$$

They add more weak bosons but leave all of the low energy predictions of the standard theory unchanged. These models have two new parameters added to the single parameter of the standard model, $\sin^2\theta_W$. These two parameters can be chosen to be M_1 and M_2, the masses of the two neutral bosons in the model. The coupling strength of the two bosons will depend on M_1 and M_2. C can then be expressed in terms of the model parameters.

In SU(2) x U(1) x U(1)

$$C = \cos^4(\theta_W) \left(\frac{M_{Z^0}^2}{M_1^2} - 1 \right) \left(1 - \frac{M_{Z^0}^2}{M_2^2} \right) \tag{10}$$

and in SU(2) x U(1) x SU(2)

$$C = \sin^4(\theta_W) \left(\frac{M_{Z^0}^2}{M_1^2} - 1 \right) \left(1 - \frac{M_{Z^0}^2}{M_2^2} \right) \tag{11}$$

Fig. 21 shows the limits placed by our measurement on the parameter space for these two models. For SU(2) x U(1) x U(1), the 95% confidence level limit requires that one of the two Z's has a mass very close to the standard M_Z. The other may have a very large mass or may actually have a small mass, in which case, one finds that its coupling strength becomes very small. For SU(2) x U(1) x SU(2), the constraint is not as tight, but about half of the parameter space has been eliminated.

III. ELECTROWEAK REACTIONS OF QUARKS

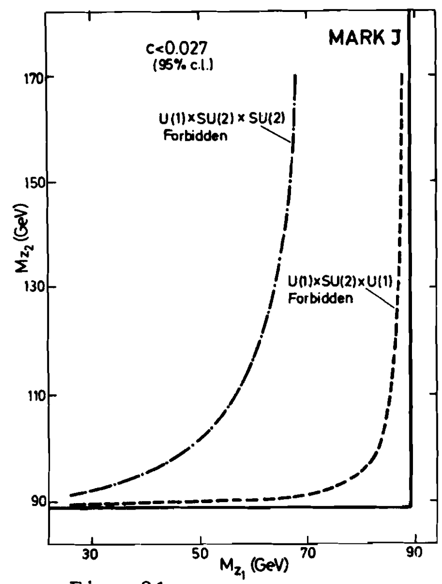


Fig. 21

Determination of $\sin^2\theta_W$

The data in e^+e^- on production of hadrons can also be used to test the electroweak interaction[14]. In particular, the total hadronic cross section is sensitive to weak effects. The ratio of the total hadronic cross section, corrected for QED radiative effects, to the lowest order QED cross section for the production of muon pairs is known as R. R is just the sum over flavors and colors of R for each quark species.

$$R = \sum_{\substack{\text{Flavors} \\ \text{Colors}}} R_q$$

To lowest order, R_q is

$$R_q = Q_q^2 - 8sg\, Q_q g_{V_e} g_{V_q} \left(\frac{M_Z^2}{s-M_Z^2} \right) + 16 s^2 g^2 \times$$

$$(g_{V_e}{}^2 + g_{A_e}{}^2)(g_{V_q}{}^2 + g_{A_q}{}^2)\left(\frac{M_Z^2}{s-M_Z^2} \right)^2 \tag{13}$$

where

$$g_{A_q} = T_{3_q} = \pm \frac{1}{2}$$

and

$$g_{V_q} = T_{3_q} - 4Q_q \sin^2\theta_W$$

is, in the standard model, approximately 0.19 for charge 2/3 quark and -0.35 for charge 1/3. This is in contrast to the charged leptons, where $g_V \approx -0.08$. Calculations of the weak effects on quark production can be found in Ref. 15. Of course there is also a well known QCD correction[16] to R.

$$R_q \to R_{q_0} \left| 1 + \frac{\alpha_s}{\pi} + \ldots \right|$$

This correction is taken account of in the analysis but the results are insensitive to the value of α_s.

In Fig. 22, measurements of R at a wide range of center of mass energies are compared to the predictions for different values of $\sin^2\theta_W$. The data agree well with the best fit for value of $\sin^2\theta_W$ of 0.29 but clearly disagree with the other values of $\sin^2\theta_W$ shown. Even though the systematic error on the measurement of R is large, the point to point error is estimated to be quite small, so that by measuring the energy dependence of R, we can make a good determination of weak effects. PETRA has recently run at center of mass energies of 14 and 22 GeV, yielding high statistics measurements of R at those energies. From these data, along with the data on leptons from the previous section, we get a preliminary value from MARK-J of

$$\sin^2\theta_W = 0.27 \begin{smallmatrix}+0.06\\-0.04\end{smallmatrix}$$

or at the 95% confidence level

$$0.19 < \sin^2\theta_W < 0.39.$$

This is now a very accurate determination of $\sin^2\theta_W$ at high q^2, $q^2 \approx 1300$ GeV^2. Using a similar analysis, JADE has obtained a value from their combined data of $\sin^2\theta_W = 0.22\pm0.08$.

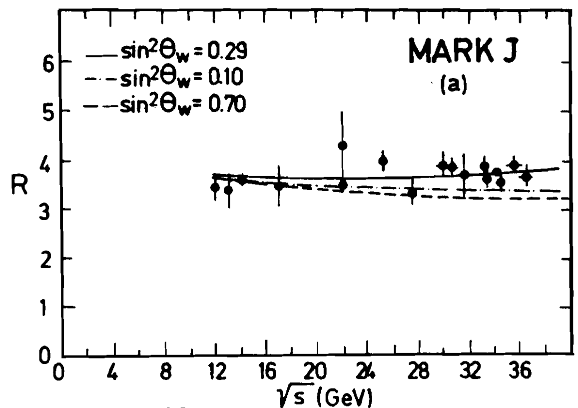


Fig.22

Bounds on Weak Angles

By putting an upper limit on the B particle lifetime, measured in events containing muons, JADE has deduced a limit on the weak mixing angles. In their formalism, decays of a b quark to a u quark are proportional to $\sin(\beta)$ and decays to a c quark are proportional to $\sin(\gamma)\cos(\beta)$. The lifetime of the particle is then influenced by these angles, being longer if both $\sin(\gamma)$ and $\sin(\beta)$ are small. Fig. 23 shows their bounds on the angles derived from their determination that the lifetime is less than 5×10^{-12} sec. The upper limit on the angles comes from high accuracy measurements of the Cabibbo angle in different processes. Since the figure is drawn on a log scale, it should be noted that there is still a very large amount of freedom for these angles.

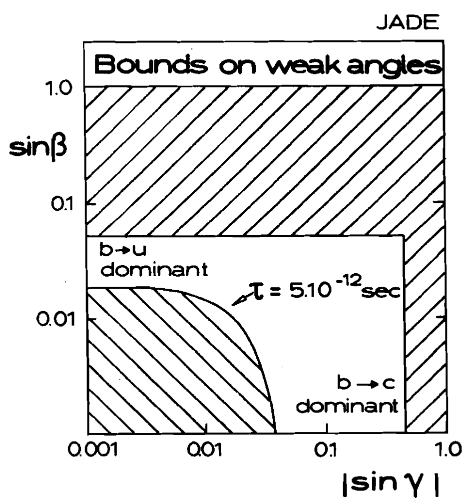


Fig. 23

Production of Leptons in Hadronic Events

The leptons in hadronic events can give us much information about the electroweak production of heavy quarks and about their weak decays. An experimental program to understand these leptons is under way at PETRA. The primary goal of this is to measure the forward-backward charge asymmetry in the production of heavy quark pairs. Since this asymmetry is inversely proportional to the quark charge, the asymmetry expected for charmed quark production is 50% larger than for muon pairs and the asymmetry for bottom is a factor of three larger. The asymmetry in production of heavy quarks is transmitted into a charge asymmetry in their decay muons. Two of the papers contributed[17] to this session address this subject.

Of course the leptons from heavy quark decay may allow us to measure several other quantities of interest, such as the charm and bottom fragmentation functions and the semileptonic decay branching ratios for charm and for bottom. I will report on a preliminary determination of the semileptonic branching ratio for bottom to indicate how the charm and bottom flavors can be separated even at high energy.

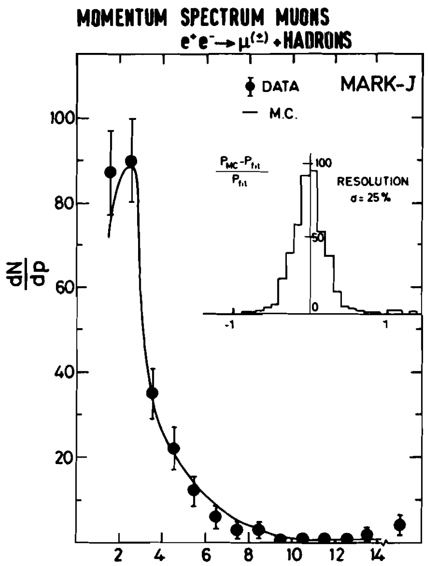


Fig. 24

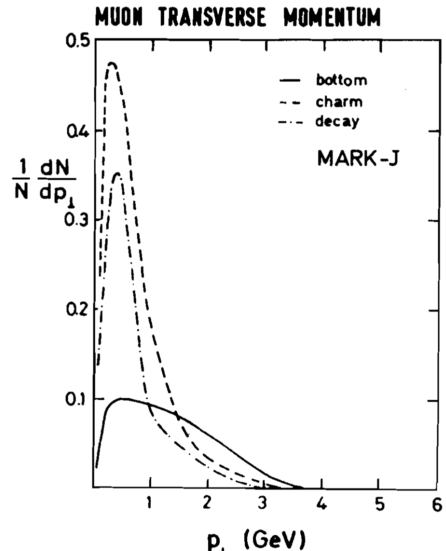


Fig. 25

First, to show that the fragmentation functions can be tuned up to fit the data, the momentum distribution of muons in hadron events is shown in Fig. 24. The detector used, MARK-J, has a minimum momentum cut off of around 1.3 GeV imposed by the requirement that a muon, to be identified, must pass through the entire hadron calorimeter and be momentum analysed using the outside muon chambers.

To make a partial separation of the muons from bottom decay, we look at the transverse momentum of the muons with respect to the jet axis of the jet containing the muon. Since transverse momentum due to fragmentation is small, the muon transverse momentum will largely come from the kick received in the decay of the massive parent particle. Fo a B particle decay, the average transverse momentum is considerable, around 1 GeV. In Fig. 25, the Monte Carlo P_t distribution of muons from three sources are shown. Although the B decay events are only a small part of the inclusive muon event sample, when a cut of $P_t > 1.2$ GeV is applied, we find that we can enrich the fraction from bottom to 45% of the total. This means, we can use the rate of events with P_t greater than 1.2 GeV to measure the bottom semileptonic branching ratio. In Fig. 26, the measured P_t distribution is compared to what we expect according the the Monte Carlo, assuming a $B \to \mu + X$ branching ratio of 8%. The agreement over the entire distribution is quite good. Using the rate for $P_t > 1.2$ GeV then, we find

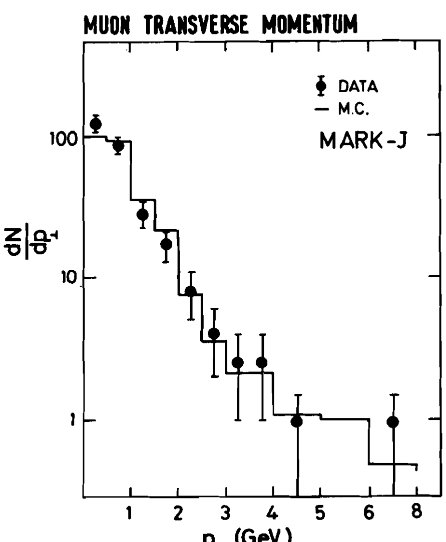


Fig. 26

PRELIMINARY

$$Br\ (B \to \mu + X) = 8.0\% \pm 2.7\% \text{ statistical} \quad \pm 2.0\% \text{ systematic}$$

where this branching ratio refers only to the primary decay of a B particle to a muon, not to muons from the cascade decay through charm. In the future, we hope to improve

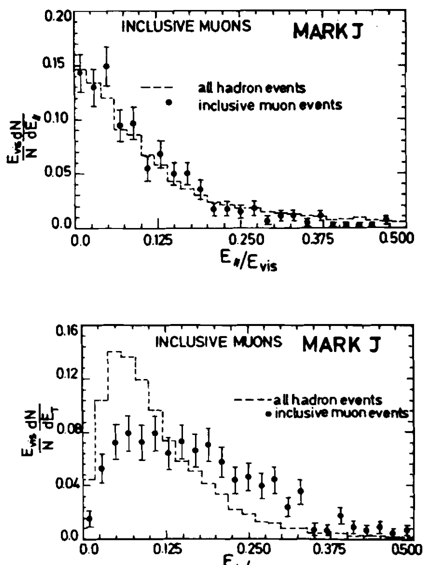


Fig. 27

this flavor separation perhaps by including jet variables. Another possibility is to look for missing neutrinos also at high P_t. In Fig. 27, the energy imbalance along the beam and perpendicular to the beam for inclusive muon events is compared to that for all hadron events. The inclusive muon events are seen to be substantially more imbalanced perpendicular to the beam, where the muon detection is concentrated, than are the standard events. This is due to missing neutrino energy along with some contribution from muon energy escaping from the calorimeter.

IV SEARCH FOR STRUCTURE IN THE FERMIONS

The data presented previously, on production of charged leptons, can be used to search for structure in the fermion by looking for a q^2 dependence to the cross sections that is not expected. In this measurement, we assume that the standard weak model is correct or at least that weak effects are nearly as small as in the standard model. Similar results[18] have been presented before. One new item of data is shown in Fig. 28. Here the measurements of R are used to look for structure in the quarks. A breakdown of the pointlike behaviour of any of the fermions is parameterized in terms of a form factor with one parameter, Λ[19].

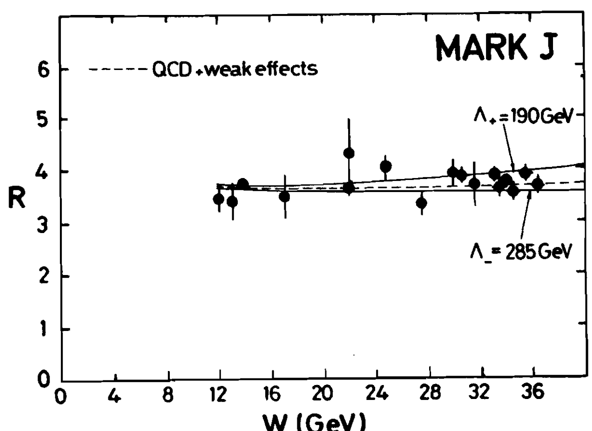


Fig.28

$$F_{\pm} = 1 \mp \frac{q^2}{q^2-\Lambda_{\pm}^2} \qquad (14)$$

The + and - refer to two different form factor, one of which increases the cross sections and one of which decreases them. Lower limits on $\Lambda_{\pm}$ at the 95% confidence level have been compared for each type of fermion. In Fig. 28, curves for the limiting values of $\Lambda_{\pm}$ are compared to the data to demonstrate the effect of such form factors.

Table V lists the values for the Λ parameters.

TABLE V - 95% C.L. LOWER LIMITS OF $\Lambda_{\pm}$

	e		μ		τ		q	
	Λ_+	Λ_-	Λ_+	Λ_-	Λ_+	Λ_-	Λ_+	Λ_-
CELLO	83	155			139	120		
JADE	112	106	142	126	111	93		
MARK-J	128*	161*	194	153	126	116	190*	285*
PLUTO	80	234	107	101	79	63		
TASSO	140	296	127	136	104	189		124

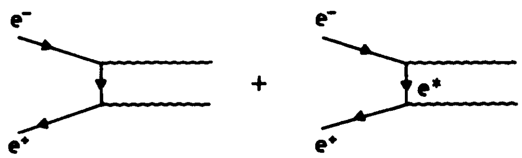
*Includes weak effects.

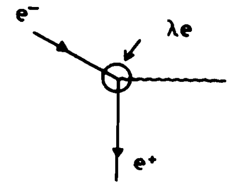
None of the fermions show evidence of structure up to energy scales of around 150 GeV.

Another way to look for structure is to look for excited states of the fermions. This has been done for the electron and muon. A heavy electron[20] would influence the process

$$e^+e^- \rightarrow \gamma\gamma$$

by adding an extra diagram containing a virtual e*. The coupling at the e^- - e* vertex is, however, a free parameter which depends on the nature of the excited state. We assume a coupling constant λ which is dimensionless as it is a ratio to e.





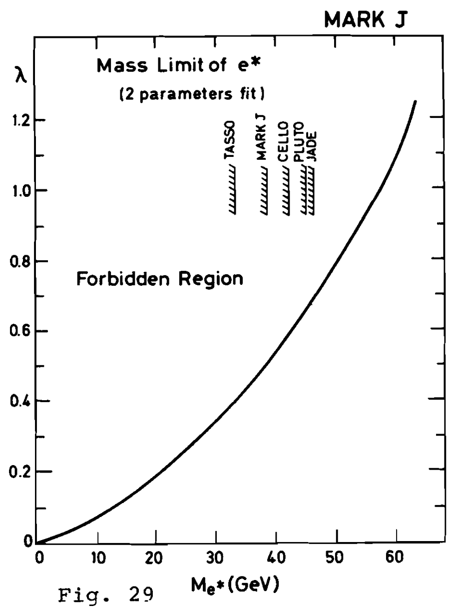


Fig. 29

Fig. 29 shows that the limits placed by the measurement of $e^+e^- \rightarrow \gamma\gamma$. The line is a 95% confidence level limit, the region to the left of the line is forbidden. Previous limits assuming that $S << M^2_{e^*}$ are shown as limits on the e* mass near $\lambda = 1$ to which they roughly correspond.

An excited muon has been looked for in two production processes.

$$e^+e^- \rightarrow \mu^{*+}\mu^{*-} \qquad\qquad e^+e^- \rightarrow \mu\ \mu^*$$
$$\mu^{*-} \rightarrow \mu^-\gamma, \quad \mu^{*+} \rightarrow \mu^+\gamma \qquad\qquad \mu^* \rightarrow \mu^\pm\gamma$$

In the first process, the coupling is near to that for production of any charged fermion, so absolute limits can be placed in the mass. This is shown in Fig. 30, where the numer of events expected from μ^* production is plotted as a function of the μ^* mass. This puts a limit on the mass

$$M_{\mu^*} > 10 \text{ GeV}.$$

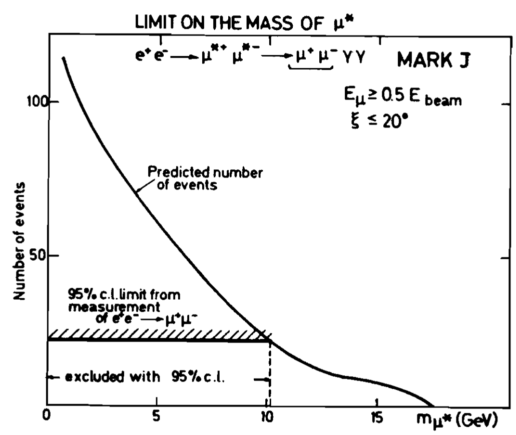
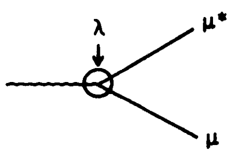


Fig. 30



In the second process, again the coupling at the vertex is not known.

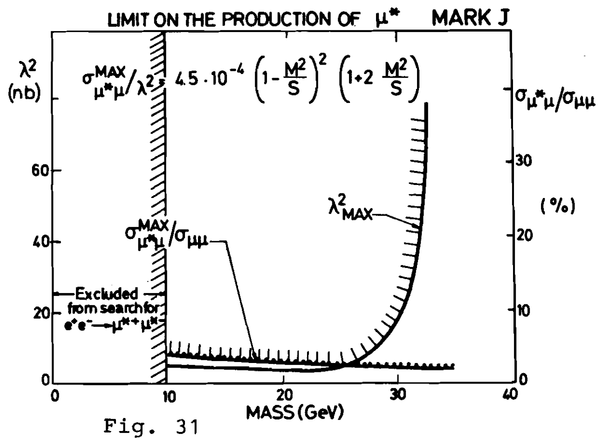


Fig. 31

Fig. 31 shows the 95% confidence level limit on λ^2 and $M_{\mu*}$. Also shown is the limit on the ratio of $\sigma_{\mu*\mu}/\sigma_{\mu\mu}$. This ratio is limited to only a few percent.

V SUMMARY

Weak effects have been observed for the first time at PETRA in the forward-backward charge asymmetry in muon pair production.

$$A_{\mu\mu} = -7.7\% \pm 2.4\% \text{ expecting } -7.8\%.$$

The expectation is that from the Glashow-Weinberg-Salam model. This highest q^2 test of the model lends strong support to the existence of the Z^0 boson. The charged lepton coupling constants g_A and g_V have been measured in purely leptonic processes at high q^2 and are found to be in agreement with the predictions of the standard theory and also with the low q^2 measurements in neutrino electron scattering,

$$|g_A| \simeq 0.50$$
$$|g_V| \simeq 0.0$$

A limit on more general weak interaction models has been made in terms of the normalized difference between the real theory and the standard theory.

$$C < 0.027$$

This limit is of interest to any model with more neutral current structure than a single Z^0 boson.

Using quarks along with the leptons we have made a high q^2 measurement of $\sin^2\theta_W$.

$$\sin^2\theta_W = 0.27 \begin{matrix} +0.06 \\ -0.04 \end{matrix}$$

We have begun to look at the weak interactions of the heavy quarks. A first result is found that

$$Br\ (B \to \mu + X) = 8\% \pm 2.7\% \pm 2\%$$

where the second error is systematic.

We find that the fermions are pointlike with no evidence of structure up to the energy scale of 100-200 GeV.

Further results on the subjects of QED tests and weak neutral current effects in e^+e^- can be found in previous reviews[21] on these subjects from which I have benefitted.

ACKNOWLEDGEMENTS

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Discussion

Y.S. Tsai, SLAC: Higher order (α^4) electromagnetic cross section in the e^+e^- reactions are not negligible. The non infrared part of the vertex and the vacuum polarization diagrams should be included in the bremsstrahlung diagrams as well as the elastic diagrams. This increases the lowest order bremsstrahlung cross section by about 20 %. This effect will, for example, decrease the value of R by about 4 %. The higher order effects also affect the asymmetry (see my contributed paper to this conference). Another interesting effect discussed in my paper is that as much as half a unit in R claimed by experimentalists could be due to emission of high energy γ at large angles by the initial e^+ or e^- and subsequent annihilation of e^+e^- at low energy with huge cross sections. The last observation depends upon whether these events are counted as hadronic events.

G. Branson: The size of corrections due to bremsstrahlung diagrams, and therefore due to vacuum polarization in bremsstrahlung diagrams, depends upon the details of experimental cuts. For R the size of bremsstrahlung corrections is less than 10 % - after typical cuts. This means that your order α^4 correction may be around 2 %. The second effect, hard photon emission, is included in our radiation correction and the experimental cuts on these unusual events are completely simulated.

H. Ogren, Indiana University: How significant is your test of the standard model in the quark sector? Does the value of $\sin^2\theta_W$ in the quark sector reflect the quark sector only or the combined leptonic-quark effects? Have you tried a fit using the value of $\sin^2\theta_W$ you obtained in the lepton sector to obtain a limit only for the quark sector?

G. Branson: Our value of $\sin^2\theta_W$ comes from the hadronic data only which means it has effects from both the quark sector and the leptonic sector because we have leptons in the initial state. We haven't made a fit using only the quark sector.

E. Barbiellini, CERN: In the g_A-g_V-plane you have used the old data of $\bar{\nu}_\mu$-e-scattering and I hope that in the final version you will use the more recent results.

G. Branson: Yes, I will try to use the most up to date results.

W.K.H. Panofsky, SLAC: Since you only used the linear q^2 term in the analysis of the $e^+e^- \to \mu^+\mu^-$ asymmetry, why is there so much emphasis on the large q^2 coverage? Please, show some data on the angular distribution and the number of events therein on which the quoted $\mu^+\mu^-$-symmetry was based.

G. Branson: The expected values of the asymmetry were calculated using the full q^2 dependence not only the linear term. Also the measured value will stand by itself as tests of models like Prof. Marshak's where one would expect a different asymmetry

The distributions from JADE, MARK-J, and TASSO are included in these proceedings, each has about 800 events.

H. Fritzsch, Univ. of Munich: I would like to remark that the parameter C deviates from 0 not only in the multiboson gauge models you have discussed in your talk, but also in models in which leptons and quarks are composite objects. In such models the neutral current channel at high energies is dominated by the continuum of the lepton-quark constituents. Thus the C parameter is different from zero. Of course, C depends on the onset of the continuum. If the latter is in the range between 100 and 200 GeV, the C parameter could be observed in the future PETRA or PEP experiments.

G. Branson: Yes. That is why I attempted to emphasize the limit on C rather than the individual models.