EXPERIMENTAL LIMITS ON THE STRENGTH OF WEAK NEUTRAL CURRENTS IN LEPTON PAIR PRODUCTION AT PETRA ENERGIES

JADE Collaboration

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The processes $e^+e^- \to e^+e^-$ and $\mu^+\mu^-$ have been studied at PETRA using the JADE detector. The data, which were collected at s-values of up to 1300 GeV^2 have been analysed in terms of an electro-weak extension of QED to obtain values for the weak vector and axial vector couplings in the lepton sector. The values obtained agree with the predictions of the standard Salam–Weinberg model and the data are further analysed in terms of this model to obtain the limits $0.10 < \sin^2\theta_W < 0.40$ (68% CL). The mass of the neutral weak gauge boson is deduced to be greater than 51 GeV/c^2.

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The energies currently available at PETRA (up to $s = 1300\ \mathrm{GeV}^2$) allow weak neutral current effects to be observed in e^+e^- scattering and annihilation for the first time. For example, a forward–backward asymmetry of about −7% is expected in the angular distribution for the process $e^+e^- \to \mu^+\mu^-$ on the basis of the standard Salam–Weinberg model. Moreover, although the Salam–Weinberg (S–W) model has been firmly established at small momentum transfers (Q^2), some crucial tests still await the model, not least the discovery of a gauge boson at a mass which corresponds to the value of $\sin^2\theta_\mathrm{w}$ determined at low Q^2.

An important test of the standard electro-weak model can be made by measuring e^+e^- and $\mu^+\mu^-$ production at PETRA energies, since the model will be tested in a new type of reaction and at the highest values of Q^2 yet available for neutral current studies. In addition, the weak couplings can be determined for the lepton sector in a model independent way and free from hadron uncertainties.

We have analysed our data for the reactions

$$e^+e^- \to e^+e^-, \tag{1}$$

$$\to \mu^+\mu^-, \tag{2}$$

in terms of an electro-weak extension of pure QED. Although the statistical (and systematic) accuracy of the data presently available from PETRA experiments does not allow a precise determination of the neutral current parameters, the data can be used to place tight limits on the allowed deviation from QED, on the values of the vector and axial vector coupling constants and on the mass or masses of the weak gauge boson or bosons. The data used for reaction (1) in this analysis include those from an earlier publication at $s \approx 1000\ \mathrm{GeV}^2$ [1], together with additional data at s up to $1300\ \mathrm{GeV}^2$. The data for reaction (2) are presented for the first time.

The experiment was carried out using the JADE detector at the e^+e^- colliding beam facility PETRA at DESY. A detailed description of the detector has already been published [2]. Both electron and muon pairs were observed in the inner drift chamber detector and apart from a fraction (15–30%) of the electrons which radiated visibly, electrons and muons were indistinguishable in the drift chamber itself. Electron pairs were selected and identified using an array of lead glass shower counters which consists of 2712 separate blocks and which surrounds the interaction point, covering the regions of polar angle θ: $|\cos\theta| < 0.82$ (barrel) and $0.89 < |\cos\theta| < 0.97$ (end caps). The lead glass provided a measurement of the electron energy and the fine granularity of the elements also allowed an accurate determination of the electron direction (typically $\Delta\theta = \pm 0.4°$ using the known interaction point) which could be matched with the track in the inner detector. The details of the selection of the e^+e^- events have been described elsewhere [1]. The final sample consisted of 8926 events within the fiducial region $|\cos\theta| < 0.76$, corresponding to an integrated luminosity of $7920\ \mathrm{nb}^{-1}$. The muon filter, which consists of a segmented iron and concrete absorber with particle track determination between the various segments, has been described in detail elsewhere [3]. For the purposes of this analysis, it was used as a final check on the selection of muons.

Events of the type $e^+e^- \to \mu^+\mu^-$ were selected from the 2 prong sample according to the following criteria:

1. Collinearity better than 200 mr. This was matched in the corresponding calculation of the radiative corrections [4].
2. Both tracks must enter the fiducial volume of the lead glass detector and deposit less than one third of the beam energy.
3. To reject cosmic rays, the difference in flight time measurement from the TOF counters must be less than 4 ns and the flight time of each track must be within ±3 ns of the beam crossing. The residual cosmic ray background was estimated to be less than 1%.
4. The sum of the momenta of the two tracks determined by the inner detector must be greater than 40% of the summed beam energies. This loose cut completely removed the background from two-photon processes.

The events which survived these cuts were scanned visually and the compatibility of the pattern in the muon filter drift chambers was checked. The efficiency of the above cuts was estimated to be 91%, for which a correction was applied. A further 2% correction was made for residual $\tau^+\tau^-$ contamination. The errors are mainly statistical with an estimated systematic normalisation uncertainty of less than 5%. The final sample of 240 $\mu^+\mu^-$ events corresponded to an integrated luminosity of $6850\ \mathrm{nb}^{-1}$

The charge of the final state electrons (or muons) was determined by the measured curvature of the track in the 5 kG solenoidal field. In some cases, however, one of the pair could sometimes be assigned the wrong charge resulting in a doubly positive or negative pair. This error was due to the finite momentum resolution and to radiative effects which made an otherwise simple collinear pair appear to have a more complex pattern. A statistical analysis was used to calculate the probability of charge misidentification p_c and to resolve ambiguous events. If n_F, n_B and n_A are the observed numbers of events in a particular angular bin of $|\cos\theta|$ with the e^- (μ^-) forward (F), backward (B) and ambiguous (A), then the true numbers N_F and N_B and the probability p_c are related by the following three equations:

$$n_F = N_F(1-p_c)^2 + N_B p_c^2,$$

$$n_B = N_F p_c^2 + N_B(1-p_c)^2,$$

$$n_A = (N_F + N_B)\,2p_c(1-p_c),$$

which can be solved for the three quantities N_F, N_B and p_c. The value of p_c was typically 5–10% for electrons, whereas for muons, which do not radiate, p_c was less than 2%.

The luminosity was determined independently in the end cap lead glass counters ($\cos\theta \approx 0.95$) and in the small angle tagging counters ($\cos\theta \approx 0.999$) by measuring the rate for the process $e^+e^- \to e^+e^-$. At these small angles, the process is completely dominated by t-channel single photon exchange and the cross section can be calculated ignoring weak effects, although radiative effects were taken into account as described in ref. [1]. The two measurements of the luminosity agreed within ±2.5% and this was taken as an estimate of systematic uncertainties and included in the error propagation. The end cap luminosity was used for this analysis.

The differential cross sections for the two processes were calculated and the results are shown in fig. 1.

Most of the data were taken in the form of a scan in steps of 20 MeV in the CMS energy. In fig. 1, the data have been averaged over the whole energy region whereas fig. 2 shows the ratio of the wide angle Bhahba events to the number expected from QED on the basis of the end cap luminosity measurement. The ratio in fig. 2 is plotted as a function of energy in steps of 40 MeV. The presentation is particularly sensitive to an

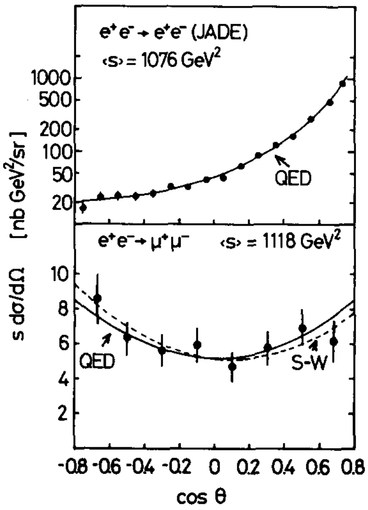

Fig. 1. The differential cross section for the processes $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$. The solid curves show the prediction of lowest order QED and the dashed curve shows the prediction for $e^+e^- \to \mu^+\mu^-$ in the standard Salam–Weinberg model. Radiative corrections have been applied to the data.

axial vector of low mass Z^0, which would leave the QED cross section at $\cos\theta \approx 0.95$ relatively unaffected. Since a low mass gauge boson with conventional coupling would produce a large increase in yield (ratio $\approx 10^3$), the existence of even an unexpectedly narrow Z^0 in the PETRA energy range can clearly be ruled out. The $\mu^+\mu^-$ angular distribution was used to determine the forward–backward asymmetry A =

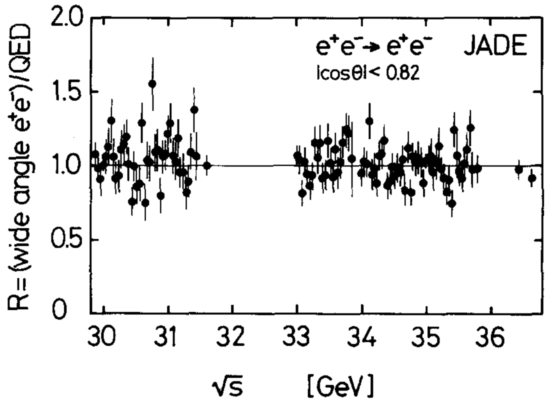

Fig. 2. The energy dependence of the ratio of wide angle $e^+e^- \to e^+e^-$ events to the number expected on the basis of the small angle luminosity measurement and pure QED.

$(F-B)/(F+B)$ over the θ range covered by this experiment ($|\cos\theta| < 0.75$). The value obtained was $A = (-5\pm6)\%$. It is worth noting that second order QED processes at this energy introduce a positive asymmetry of 2%, i.e. in our raw data, before radiative corrections, the two asymmetries cancel each other to produce a net asymmetry of −3%. The measured value is insensitive to inefficiencies or biases in the detector or trigger which affect positive or negative particles equally, since such effects cancel out. This value for the asymmetry can be compared with the value of −6% expected from the standard S–W model. (The S–W asymmetry would be −7% over the full angular range.)

Assuming μ–e universality, a generalised electroweak formulation of the differential cross section [5] can be written as follows, for $e^+e^- \to \mu^+\mu^-$,

$$(8s/\alpha^2)\,\mathrm{d}\sigma/\mathrm{d}\Omega = (B_3 + B_2)(1+\cos^2\theta) + 2(B_3 - B_2)\cos\theta, \tag{3}$$

where

$$B_2 = |1 + (g_v^2 - g_a^2)R|^2$$

and

$$B_3 = \tfrac{1}{2}\,[|1 + (g_v + g_a)^2 R|^2 + |1 + (g_v - g_a)^2 R|^2],$$

with a similar but more complex relation [5,6] for $e^+e^- \to e^+e^-$. The vector and axial vector couplings g_v and g_a are normalised so that in the standard S–W model, $g_v = \frac{1}{2}(1 - 4\sin^2\theta_w)$ and $g_a = -1/2$. Curves corresponding to pure QED ($g_v = g_a = 0$) and the standard S–W model are shown in fig. 1 for comparison.

If the weak neutral current is mediated by a single gauge boson of mass m_Z and width Γ_Z, then,

$$R = \sqrt{2}G_F m_Z^2 s/e^2(s - m_Z^2 + \mathrm{i}m_Z\Gamma_Z), \tag{4}$$

where G_F is the Fermi weak coupling constant [$= 1/(293\ \mathrm{GeV})^2$]. It follows that the existence of a Z^0 with a mass above the energy range covered by this experiment would still produce observable effects. For example, the forward–backward angular asymmetry in $e^+e^- \to \mu^+\mu^-$, which is −6% in our detector for $m_Z = 90$ GeV, would increase to a value of −20% if the Z^0 had a mass of 50 GeV. Sakurai has suggested [7] a comparison of data with a non gauge invariant version of the above formalism where m_Z is a free parameter (not constrained by $\sin^2\theta_w$) but where all the couplings (and hence $\sin^2\theta_w$) are fixed at their low Q^2 values of $g_v = 0.04$ and $g_a = -1/2$, corresponding to a value of $\sin^2\theta_w = 0.23$. A comparison of our $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$ data with this type of formula leads to the limit:

$m_Z > 51\ \mathrm{GeV}/c^2$ with 95% confidence level.

Gauge invariant extensions of the standard SU(2) × U(1) weak theory which contain more than one neutral gauge boson have been proposed by a number of authors [8–10]. Two recent models [8,9] have the property that they predict the existence of two neutral gauge bosons with masses which are respectively lower and greater than the standard S–W Z^0 mass: $m_1 < m_Z(\mathrm{S–W}) < m_2$, without predicting the values of the masses. These gauge invariant extensions can be characterised by a modified interaction hamiltonian:

$$H = (4G_F/\sqrt{2})\,[(j_3 - \sin^2\theta_w\, j_{em})^2 + Cj_{em}^2],$$

where the positive definite coefficient C represents the deviation from a single gauge boson model. It has been shown [7,8] that the coefficient C corresponds to a modification of the vector coupling as follows:

$$g_v^2 \to \tfrac{1}{4}(1 - 4\sin^2\theta_w)^2 + 4C,$$

with

$$g_a^2 = \tfrac{1}{4}$$

as before. The analytic form of C then depends on the gauge group, e.g. in the case of the SU(2) × U(1) × U(1)′ model of de Groot et al. [8],

$$C = \cos^4\theta_w\ (m_2^2 - m_Z^2)(m_Z^2 - m_1^2)/m_1^2 m_2^2.$$

If $\sin^2\theta_w$ is assumed to be 0.23, then an analysis of our e^+e^- and $\mu^+\mu^-$ data in terms of C (and m_1 and m_2) leads to the limit:

$C < 0.039$ with 95% confidence level.

The data also restrict the possible values for the masses m_1, m_2 of the two bosons within the context of the models of the Groot et al. [8] and Barger et al. [9]. This is shown in fig. 3 where the shaded areas to the right of the curves are the only allowed regions (95% CL) for possible mass values for m_1 and m_2.

In the absence of direct evidence for a gauge boson with a mass significantly lower than that of the standard S–W Z^0, eq. (4) can be modified by making the approximation $s \ll m_Z^2$, then $R = -\sqrt{2}G_F s/e^2$, thus recovering the traditional Fermi point coupling. Val-

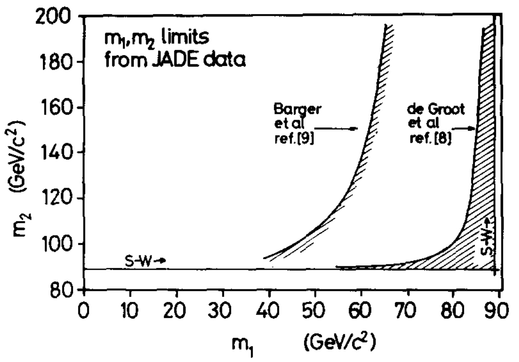

Fig. 3. The allowed regions for m_1, m_2 (shaded areas) from a fit to the models of de Groot et al. and Barger et al. The standard S–W model corresponds to the lines at $m_1 = 90$ GeV/c^2 and $m_2 = 90$ GeV/c^2 ($\sin^2\theta_w = 0.23$).

ues for g_v^2 and g_a^2 were obtained by fitting the resulting form for the differential cross section to the data. Statistical and systematic errors were propagated as described in ref. [1]. The results of this fit [6] ‡1 were:

$$g_v^2 = 0.01 \pm 0.08, \quad g_a^2 = 0.18 \pm 0.16,$$

while g_v^2(S–W) = 0.0016, for $\sin^2\theta_w = 0.23$ and g_a^2(S–W) = 0.25. The results are plotted in fig. 4 together with the values found by Barber et al. [11] and the predictions of the standard S–W theory. Our results favour

‡1 Looser constraints on g_v^2 and g_a^2 have been obtained using Mark J data in ref. [11].

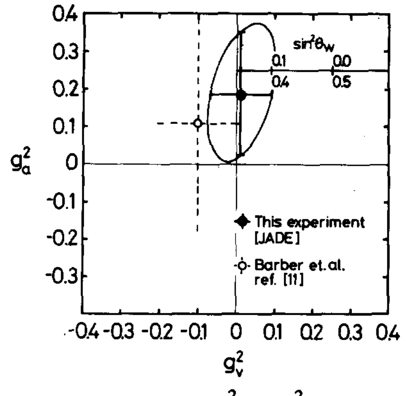

Fig. 4. The measured values of g_v^2 and g_a^2 from this experiment. Also shown is the result of Barber et al. Pure QED corresponds to $g_v^2 = g_a^2 = 0$ and the standard S–W model corresponds to the line at $g_a^2 = 0.25$ ($g_v^2 > 0$).

the dominant axial vector solution obtained from an analysis of ν–e and ν–hadron scattering [12]. Our best fit had $\chi^2 = 49.2$ for 54 degrees of freedom compared with $\chi^2 = 50.3$ for pure QED ($g_v^2 = g_a^2 = 0$), i.e. both hypotheses are almost equally acceptable.

Since the g_v^2 and g_a^2 values obtained are consistent with those of the standard S–W model, a fit for $\sin^2\theta_w$ was made by setting $g_a^2 = 1/4$ in eq. (3) and putting $g_v^2 = \frac{1}{4}(1-4\sin^2\theta_w)^2$ and $m_Z^2 = (37.3)^2/\sin^2\theta_w(1-\sin^2\theta_w)$. The result was as follows:

$$0.04 < \sin^2\theta_w < 0.46, \quad 95\%\ \mathrm{CL}$$

$$0.10 < \sin^2\theta_w < 0.40, \quad 68\%\ \mathrm{CL}\ (1\ \mathrm{sd}).$$

The ability to place tight limits on the values of g_v^2, g_a^2 and $\sin^2\theta_w$ with data which is also consistent with pure QED is analogous to the situation in $\bar{\nu}_e$–e scattering. A non zero value of g_v^2 would produce large effects which are not observed in the data. The central value of $\sin^2\theta_w$ (≈ 0.25) is therefore largely determined by the condition $1-4\sin^2\theta_w = 0$ and statistical fluctuations around a null vector coupling.

The values for the vector and axial vector weak coupling constants thus derived are in agreement with the predictions of the standard SU(2) × U(1) S–W theory and a fit within the framework of this model produces a value of $\sin^2\theta_w$ which agrees with the current world average [12]. The mass of the weak boson, with minimal assumptions, appears to be greater than 51 GeV.

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