A DETERMINATION OF QUARK WEAK COUPLINGS AT PETRA ENERGIES

JADE Collaboration

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Data on hadron production by e^+e^- annihilation at c.m. energies between 12 and 36.6 GeV have been collected using the JADE detector. They have been analysed in terms of single-photon and weak neutral-current exchange assuming production of quark–antiquark pairs with only d, u, s, c and b quarks to produce values for the quark weak neutral-current couplings. A further analysis in terms of the Glashow–Salam–Weinberg theory produced the result, $\sin^2\theta_W = 0.22 \pm 0.08$. The theory has therefore been tested in a new energy domain and within the context of the neutral weak couplings of the first, second and third generation quarks.

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The considerable research activity using e^+e^- storage rings during the last ten years has led to the conclusion that the process $e^+e^- \to$ hadrons can be regarded as quark–antiquark production via single-photon exchange with subsequent fragmentation of the quarks into hadrons. At sufficiently high energies, the fragmentation appears as a collimated jet of particles. Moreover, the most recent experiments at PETRA [1] have demonstrated that the simple picture of $q\bar{q}$ production has to be modified to first order by taking gluon emission into account.

Another feature offered by the energies now available at PETRA ($s \leqslant 1350\ \mathrm{GeV}^2$) is the possibility of studying electroweak effects in e^+e^- collisions [2]. Depending on the structure of the weak neutral current, these effects appear as a modification to the angular distribution and the total cross section for fermion–antifermion production (e^+e^-, $\mu^+\mu^-$ or $q\bar{q}$). To first order, an axial-vector neutral current introduces an asymmetry into the angular distribution which cancels out in the total cross section whereas a vector neutral current affects the total cross section rather than the shape of the angular distribution.

A study of electroweak effects in the processes $e^+e^- \to e^+e^-$ and $\mu^+\mu^-$ has already been made [3]; this paper is concerned with an analysis of data collected using the JADE detector on the process

$$e^+e^- \to q\bar{q} \to \text{hadrons}\,, \tag{1}$$

in terms of the full electroweak picture of figs. 1a–1c, including both photon and Z^0 exchange.

Detailed measurements of the total cross section and event topologies at PETRA energies [1,4] have shown that five quark flavours, d, u, s, c and b are sufficient to describe the data and that if a sixth quark exists (viz. t) then its threshold is above the energies presently available at PETRA. No resonant effects have been observed. For the purpose of this analysis therefore, it is assumed that only five quark flavours contribute to the hadronic cross section and that there are no resonant effects from these quarks in the energy range where this set of data was taken ($144 < s < 1350\ \mathrm{GeV}^2$).

The cross section for the production of a fermion–antifermion pair of electric charge Q_f, taking weak effects into account is as follows [5]:

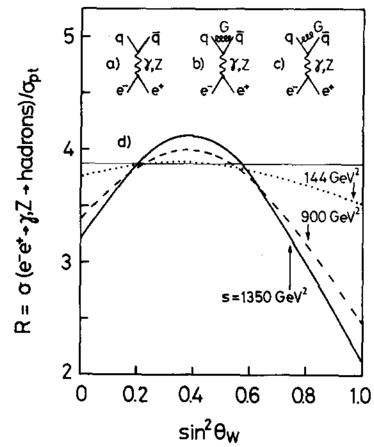

Fig. 1. (a), (b), (c), (d), e^+e^- annihilation into quark and gluon final states. The variation of the total cross section R with s and $\sin^2\theta_W$ as predicted by the Glashow–Salam–Weinberg model. The horizontal line at $R = 3.87$ corresponds to γ exchange only.

$$\begin{aligned} R_f &= \sigma(e^+e^- \to \gamma, Z \to f\bar{f})/\sigma_{pt} \\ &= Q_f^2 - 2sQ_f v_e v_f \frac{\sqrt{2}G_F}{4(4\pi\alpha)} \left[\left(\frac{s}{M_Z^2} - 1\right) + \frac{\Gamma^2}{s - M_Z^2}\right]^{-1} \\ &\quad + s^2(v_e^2 + a_e^2)(v_f^2 + a_f^2)\left(\frac{\sqrt{2}G_F}{4(4\pi\alpha)}\right)^2 \\ &\quad \times \left[\left(\frac{s}{M_Z^2} - 1\right)^2 + \frac{\Gamma_Z^2}{M_Z^2}\right]^{-1} . \end{aligned} \tag{2}$$

The total cross section is obtained by summing over all the quark flavours and multiplying by a factor 3 for colour:

$$R = 3 \sum R_f\,. \tag{3}$$

$\sigma_{pt} = 4\pi\alpha^2/3s$, G_F is the Fermi weak constant, v_e, v_f, a_e and a_f are the electron and fermion vector and axial-vector weak couplings and α is the fine structure constant. The boson structure of the weak neutral current is represented as a single pole with mass M_Z and width Γ_Z. In the limit of $s \ll M_Z^2$ and $\Gamma_Z \ll M_Z$, the square brackets in eq. (2) become -1 and $+1$, respectively. Γ_Z was set to 2.5 GeV in the analysis, although the results did not vary for $0 < \Gamma_Z < 10$ GeV. There is a corresponding equation for the forward–backward asymmetry in the angular distribution $A_f = (F - B)/(F + B)$ but it has not yet been possible to assign the primary quark charge on the basis of measured hadron jet charges. First order QCD effects can be taken into account by multiplying the whole of eq. (3) by a factor $(1 + \alpha_s/\pi)$ where α_s is the strong running coupling constant. This assumes that gluon emission from the quark lines is the same for single-photon or neutral-current exchange. A detailed study of QCD effects in this electroweak process has been made by Jersák et al. [6] who also included finite quark mass effects. Even including a mass of 5 GeV for the b quark, the difference between the simple multiplicative prescription and the correct procedure of Jersák et al. is less than 0.2% at PETRA energies, and this is too small to be observed. A calculation of eq. (3) at PETRA energies summed over all five quark flavours is shown in fig. 1d for the case of the Glashow–Salam–Weinberg (GSW) model which has been shown to be correct at low q^2. In this model, the couplings can be expressed in terms of the single parameter $\sin^2\theta_W$:

$$v_e = -1 + 4\sin^2\theta_W\,, \qquad a_e = -1\,,$$

$$v_c = v_u = 1 - \tfrac{8}{3}\sin^2\theta_W\,, \qquad a_c = a_u = 1\,,$$

$$v_d = v_s = v_b = -1 + \tfrac{4}{3}\sin^2\theta_W\,, \quad a_d = a_s = a_b = -1\,,$$

$$Q_d = Q_s = Q_b = -\tfrac{1}{3}\,, \qquad Q_c = Q_u = \tfrac{2}{3}\,.$$

Fig. 1 shows the value of R plotted as a function of $\sin^2\theta_W$ for three values of s covered by our data. It can be seen that R varies between 2.1 and 4.1 at PETRA energies, depending on the values of s and $\sin^2\theta_W$. This functional dependence is sufficiently strong for a measurement of $R(s)$ to be translated into a determination of $\sin^2\theta_W$.

A more model independent analysis can be carried out by making the assumption $s \ll M_Z^2$ in eq. (2). Then, summing over all flavours,

$$R = 3\sum R_f = 3\sum Q_f^2 + 6s[\sqrt{2}G_F/4(4\pi\alpha)]\,V + 3s^2[\sqrt{2}G_F/4(4\pi\alpha)]^2\,W\,, \tag{4}$$

where $V = v_e \Sigma\, Q_f v_f$ and $W = (v_e^2 + a_e^2)\,\Sigma\,(v_f^2 + a_f^2)$, i.e., in the absence of the ability to separate R into its separate components from d, u, s, c and b quarks, a study of electroweak effects essentially leads to a measurement of V and W. The term in G_F^2 becomes comparable to the first order term for values of $\sin^2\theta_W$ close to 0.25 when $v_e \to 0$.

The data used for this analysis are all the hadronic data collected by the JADE experiment up to the time of the November 1980 shutdown, covering the energy range $12 < 2E_{beam} < 36.6$ GeV. The details of the data collection, analysis, corrections and cross sections have already been published [4]. Use is made in this analysis of subsequent careful studies of systematic effects in the detector and further analyses which have reduced the size of the systematic error on the total cross section to the level of 7%. This represents the combined errors from all presently known sources. A further important factor is that the systematic error is believed to be independent of energy. This also allows the considerable s dependence (see fig. 1d) in the theory to be used in the determination of V and W or $\sin^2\theta_W$.

The data exist in the form of 264 independent measurements of R throughout the above energy range. Since the overall size of the data sample is 3700 events, ($\approx$14 events per point on average) the distribution of the errors on individual data points is best described by Poisson statistics. The data were fitted to the functional forms by minimising the negative log of the likelihood which was obtained from the individual Poisson probabilities

$$-2\log L = -2\sum_{264}\log P_i(R_m, R_{th})\,,$$

where $P_i(R_m, R_{th})$ is the Poisson probability of obtaining a measurement R_m from a theoretical mean of R_{th} based on the known luminosity of this ith data point. R_{th} was either eq. (3) or (4) multiplied by the factor $(1 + \alpha_s/\pi)$ where a value of $\alpha_s = 0.17$ was used, determined from event shape topologies in the same data [7]. Corrections of order α_s^2 were neglected.

A simple fit to determine a mean value for R, averaged over the whole energy range gave the result $\langle R\rangle = 3.96 \pm 0.064$, although this figure no longer contains the information on the energy dependence between $s = 144$ and $s = 1350$ GeV^2. Standard deviations in all cases were determined from an increase of 1 in $-2 \times \log L$ from its minimum value.

The major sources of systematic error in the analysis are the uncertainty in the knowledge of α_s and in the overall normalisation of the hadronic cross sections (±7%). In the case of α_s, an uncertainty of ±20% was propagated into the final fit values. The effect of the systematic error on the normalisation was taken into account (see ref. [8]) by including an additional term in the likelihood:

$$-2 \log L' = -2 \sum \log P_i(R_m, R_{th}) + [(N - 1.0)/\sigma]^2 ,$$

where $\sigma = 0.07$ is the systematic uncertainty on the normalisation. Using this procedure, a model independent fit was carried out to the form of eq. (4) to determine V and W, followed by a fit to the GSW model [eqs. (2) and (3)] to determine a value for $\sin^2\theta_W$. The best fits in both cases were obtained with a normalisation of $N = 0.985 \pm 0.03$. The 1.5% change from $N = 1.0$ is well within the 7% normalisation uncertainty and provides confidence in the calculation of the systematic errors.

The determination of V and W is shown as a 1 sd ellipse in fig. 2. Since V determines the sign of the interference term, it can in general be positive or negative. W on the other hand, is expected to be positive due to the positivity of the pure weak term, although our measurement of W extends into the negative region. The ellipse corresponds to a constraint on the quark vector and axial-vector couplings in terms of the combinations $V = v_e \sum Q_f v_f$ and $W = (v_e^2 + a_e^2) \sum (v_f^2 + a_f^2)$. The GSW model is shown as a curve in fig. 2 plotted as a function of $\sin^2\theta_W$. The point corresponding to the present world average [9], $\sin^2\theta_W = 0.23$ lies within the ellipse, indicating that our data at s up to 1350 GeV^2 agree with the low q^2 determination of $\sin^2\theta_W$.

The fit within the framework of the GSW model produced the result $\sin^2\theta_W = 0.22 \pm 0.03$, where the

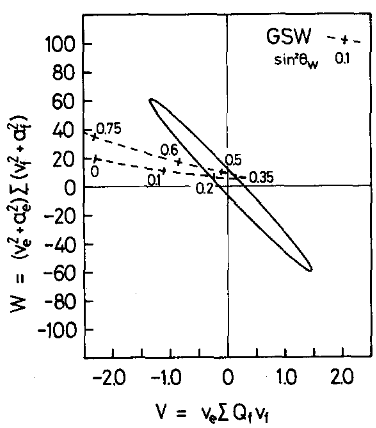

Fig. 2. The log-likelihood function contour (68% c.l.) in the V–W plane. The dashed curve shows the locus of points for the Glashow–Salam–Weinberg model.

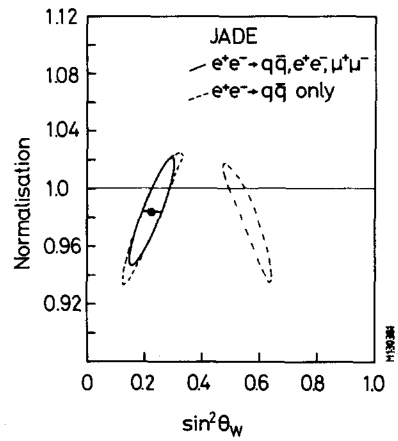

Fig. 3. The log-likelihood function contours in the $\sin^2\theta_W$–normalisation plane for hadron data (dashed line) and hadron plus lepton data (solid line). The horizontal error bar indicates the magnitude of the statistical error.

error is statistical only. The full correlation for $\sigma = 7\%$ is shown as the dashed line contour in fig. 3 (increase of 1 in $-2 \log L$). Further fits were tried varying the value used for α_s where it was found that a 20% change in α_s altered the fitted value for $\sin^2\theta_W$ by 0.03. Fig. 3 also shows that in addition to the statistical error, there is a further systematic error due to the correlation with the normalisation of about ±0.10.

A second minimum exists in the log-likelihood function (see fig. 3) at $\sin^2\theta_W = 0.56 \pm 0.03$ which cannot be excluded by this hadron data alone. An analysis of lepton pair data, however, which was collected simultaneously in the same apparatus produced the limits [3] $0.10 < \sin^2\theta_W < 0.40$ at the 1 sd level. The use of all the JADE data therefore leads to the single solution at $\sin^2\theta_W = 0.22$.

The correlation can be reduced if the χ^2 contour from the lepton pair data is added to $-2 \log L'$. The result is shown as the solid ellipse in fig. 3 (increase of 1 in $-2 \log L$) and represents a fit to the combined fermion–antifermion data measured in the JADE apparatus. The result is then: $\sin^2\theta_W = 0.22 \pm 0.08$ where the error consists of ±0.03 (statistical), ± 0.03 (α_s) and ± 0.07 (systematic) [‡1].

It seems curious that the value of $\sin^2\theta_W$ turns out

[‡1] A similar analysis of Mark J data was described by Böhm [10].

to have just that value which makes the lepton vector coupling essentially vanish, together with observable effects in the interference term in the total cross section for the production of fermion–antifermion pairs. The measurement of a statistically significant angular asymmetry in the production of $\mu^+\mu^-$ at PETRA, consistent with $a_e = a_\mu = -1$ becomes an even more crucial test of the GSW model at these energies.

To summarise, we have made the first check of the weak quark couplings in e^+e^- annihilation at high energies, a process which includes the production of heavy quarks. A model independent determination of the weak couplings was found to be consistent with the values expected in the GSW model on the basis of the low q^2 world average value for $\sin^2\theta_W$. The data were also used to determine a value of $\sin^2\theta_W = 0.22 \pm 0.08$ at $\langle s \rangle \approx 1200$ GeV^2. The theory has therefore been successfully tested in a new domain of high q^2 and in addition, in processes which involve the production of first, second and third generation quarks.

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