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# New Results on $e^+e^- \to \mu^+\mu^-$ from the JADE Detector at PETRA

JADE Collaboration

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**Abstract.** The production of collinear muon pairs has been studied using the JADE detector at the $e^+e^-$ storage ring at PETRA. Results for the total cross section and the angular distribution were obtained at centre of mass (cm) energies ranging from 12 to 46 GeV. The data correspond to an integrated luminosity of $\int L dt > 90\,\text{pb}^{-1}$, of which $71.2\,\text{pb}^{-1}$ were taken at $\langle\sqrt{s}\rangle = 34.4$ GeV and $17\,\text{pb}^{-1}$ at $\langle\sqrt{s}\rangle = 42.4$ GeV. The results are compared to electroweak theories, in particular the "Standard Model".

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## Introduction

The JADE detector [1] at the $e^+e^-$ storage ring PETRA has been used to study the production of collinear muon pairs. First results using a fraction of the presently available data have already been published [2]. In addition to the data in the barrel part of the detector which covers a polar angular region of $|\cos\theta| < 0.80$, data have now also been obtained in the forward region at an average $|\cos\theta| = 0.890$.

The production of collinear muon pairs has also been measured by the CELLO, MARK J, PLUTO and TASSO [3] collaborations at PETRA and by the MARK II and MAC [4] collaborations at PEP.

## Data Analysis

The data analysis has remained essentially unchanged compared to our previous publication [2]. The main points will be repeated for completeness. Two different triggers were used in the barrel ($30° < \theta < 150°$) and the endcap regions ($20° < \theta < 35°$ and $145° < \theta < 160°$). In the barrel part, signals from scintillation counters and the track detector triggered events with two tracks coplanar within 21°. In order to reduce the trigger rate, events were rejected with more than 6 out of the 42 scintillation counters firing. The effects of this veto signal were carefully monitored by 3 independent methods.

In the endcap region, 2 arrays of scintillation counters triggered events with two tracks at opposite ends of the detector. In addition, at least one track was required to penetrate through a segmented concrete absorber, the muon filter.

Off line, events were selected which contained at least two tracks with momenta greater than $E_b/3$, where $E_b$ was the beam energy. The tracks were required to be collinear within 0.200 rad. If they projected into the array of lead glass counters, which was the case for almost all barrel events but only for $\sim 40\%$ of the forward events, the energy deposition was limited to $E_b/3$. This cut, together with the requirement that at least one particle should penetrate at least three absorption lengths of the muon filter, eliminated background from Bhabha scattering. In fact, 87% of the particles penetrated more than 5 absorption lengths.

Background from cosmic ray muons was removed by requiring the tracks to come from a cylinder of radius 3 mm around the interaction point and, in addition, by a time-of-flight (TOF) cut.

At the highest PETRA energies, for $E_b > 20$ GeV, background due to low energy photons from synchrotron radiation strongly increased. This sometimes led to additional hits in the TOF counters before the muon could be registered. Therefore, the removal of cosmic rays was not as efficient as at low energy. This contamination, which was negligible around 17 GeV, was determined to be 3% above $E_b > 20$ GeV and subtracted statistically.

Muon pairs from two photon collisions $e^+e^- \to e^+e^-\mu^+\mu^-$ were calculated to constitute 0.7–0.8% of the events. The background from tau pair production was computed by Monte Carlo simulations to amount to 2%.

All selected events were visually scanned to verify that they correspond to the desired pattern. Remaining background – mainly due to deficiencies of the programs – was eliminated at this stage.

In order to obtain the final cross sections, corrections of typically 5–10% were applied for losses by accidental vetoes in the trigger. Furthermore the losses ($\sim 4\%$) due to the cuts applied were corrected.

Finally, radiative corrections due to QED diagrams up to order $\alpha^3$ were calculated [5, 6] using Monte Carlo programs provided by Berends, Kleiss and collaborators. The detector resolutions and cuts were taken into account. The radiative corrections were applied bin by bin to the angular distributions. The resulting correction on the total cross section is small for the cuts used, but the radiative effects cause an integrated forward backward asymmetry of $+2\%$ for $|\cos\theta| < 0.8$.

The luminosity was determined by Bhabha scattering in the barrel region, $|\cos\theta| < 0.76$. It agreed well with the luminosity derived from Bhabha scattering measured in the endcaps. A systematic uncertainty of $\sim 3\%$ is attributed to the luminosity measurement.

## Results

The results for the barrel region and the endcap region will be discussed separately. The acceptance corrected total cross sections $s \cdot \sigma_{\mu\mu}$ for the barrel region are given in Table 1 for several cm energies. A large part of the data was obtained by scanning in small steps of energy. Therefore, the columns $E_b$ and $s$ give luminosity weighted averages. The errors for

**Table 1.** Total Cross Sections for $e^+e^- \to \mu^+\mu^-$

| $E_{beam}$ (GeV) | $s$ (GeV$^2$) | $\int L dt$ (nb$^{-1}$) | Events | $s \cdot \sigma_{\mu\mu}$ (GeV$^2 \cdot$nb) | $R_{\mu\mu}$ |
|---|---|---|---|---|---|
| 6.0 | 144.0 | 106.4 | 36 | 81.45 ± 13.60 | 0.94 ± 0.16 |
| 7.0 | 197.0 | 1,462.6 | 385 | 87.63 ± 4.46 | 1.01 ± 0.05 |
| 11.0 | 484.0 | 2,405.9 | 253 | 88.55 ± 5.57 | 1.02 ± 0.06 |
| 12.5 | 628.0 | 480.1 | 46 | 100.26 ± 14.78 | 1.15 ± 0.17 |
| 15.77 | 995.3 | 3,120.4 | 154 | 87.95 ± 7.09 | 1.01 ± 0.08 |
| 16.92 | 1,145.4 | 9,127.8 | 387 | 84.36 ± 4.29 | 0.97 ± 0.05 |
| 17.30 | 1,197.1 | 20,789.0 | 947 | 83.56 ± 2.72 | 0.96 ± 0.03 |
| 17.31 | 1,198.8 | 16,520.0 | 743 | 84.54 ± 3.10 | 0.97 ± 0.04 |
| 17.44 | 1,217.3 | 15,252.8 | 748 | 91.07 ± 3.33 | 1.05 ± 0.04 |
| 17.60 | 1,239.2 | 5,852.8 | 174 | 84.30 ± 6.41 | 0.97 ± 0.07 |
| 18.80 | 1,413.6 | 2,005.6 | 94 | 97.55 ± 10.06 | 1.12 ± 0.12 |
| 21.17 | 1.793.4 | 11,163.5 | 363 | 85.26 ± 4.47 | 0.98 ± 0.05 |
| 22.96 | 2,108.6 | 3,879.1 | 114 | 89.11 ± 8.35 | 0.99 ± 0.09 |

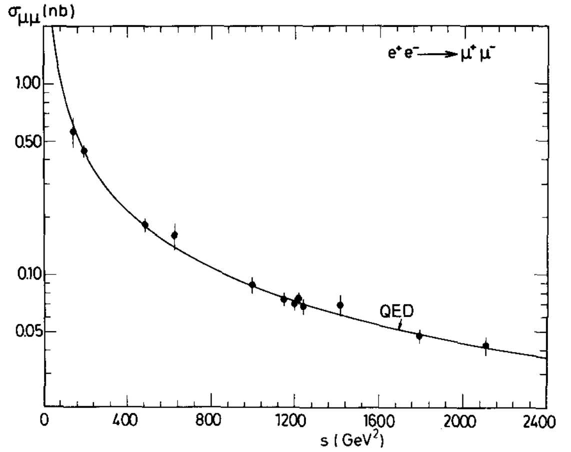


**Fig. 1.** Total cross section for $e^+e^- \to \mu^+\mu^-$ as a function of $s$, corrected for QED contributions up to order $\alpha^3$

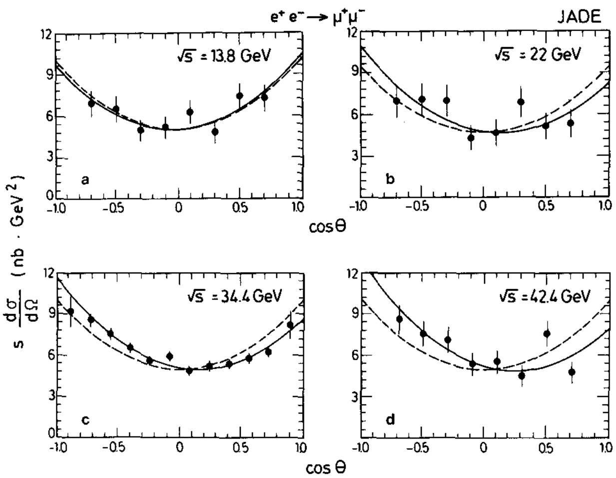


**Fig. 2a–d.** Angular distributions for $e^+e^- \to \mu^+\mu^-$ corrected for QED contributions to order $\alpha^3$ for 4 cm energies. The full lines are fits allowing for an asymmetry, the dashed lines are symmetric fits

$s \cdot \sigma_{\mu\mu}$ and $R_{\mu\mu}$, where $R_{\mu\mu} = \sigma_{\mu\mu} \Big/ \frac{4\pi\alpha^2}{3s}$ is the ratio of the total cross section to the point like QED cross section, are statistical only. The total systematic error is estimated to be 5%, which accounts for the systematic error in the luminosity determination and the event selection. The cross section $\sigma_{\mu\mu}$ is displayed in Fig. 1 as a function of $s$. The agreement with the $1/s$ behaviour predicted by QED is seen to be good.

For the angular distributions $s \cdot \frac{d\sigma}{d\Omega}$ in the barrel region which are shown in Figs. 2a–d, the data were combined into 4 energy bins. $\theta$ is defined to be the angle between the incoming positron and the outgoing positive muon. At low energies the $1+\cos^2\theta$ behaviour expected from pure QED is observed (Figs. 2a and b), but at high energies a deviation is apparent (Figs. 2c and d): the measured cross section shows an asymmetry between the forward ($\cos\theta > 0$) and backward ($\cos\theta < 0$) directions.

The measured angular distributions were fitted to the following function suggested by electroweak theories:

$$f(\theta) \sim 1 + \cos^2\theta + B\cos\theta.$$

The parameter $B$ describes the asymmetric behaviour of the data. The results of the fits are shown as full lines in Fig. 2. At the two highest energies this asymmetric fit clearly describes the data better than the one where $B$ is 0 (dashed lines).

The integrated forward-backward asymmetry is defined as:

$$A = \frac{\int_0^{+c} f(\theta)\, d(\cos\theta) - \int_{-c}^{0} f(\theta)\, d(\cos\theta)}{\int_{-c}^{+c} f(\theta)\, d(\cos\theta)} = \frac{3}{2} B \cdot \frac{c}{3+c^2}$$

where $c = \cos\theta_{\max}$ is the limit of the acceptance, which in the barrel region extends to $\cos\theta = 0.8$. The resulting asymmetries for the 4 energies are listed in Table 2. At the two highest energies, $\sqrt{s} = 34.4$ and 42.4 GeV, a negative asymmetry is observed with a statistical significance of 6.4 and 4.6 standard deviations, respectively.

In Table 2 the asymmetry extrapolated to full acceptance ($c = 1$) is also given.

The analysis of the data in the endcap region was similar to the one described above. The acceptance, which was centered around $|\cos\theta| = 0.89$, was limited by the acceptance of the trigger counters to $|\cos\theta| > 0.82$ and by the requirement of a reliable charge determination to $|\cos\theta| < 0.94$. At $\langle\sqrt{s}\rangle = 34.7$ GeV an integrated luminosity of 40.05 $\mathrm{pb}^{-1}$ was analysed and yielded 206 muon pair condidates.

The measured asymmetry at $|\cos\theta| = 0.89$ was $+(0.9 \pm 7.2 \pm 1.0)\%$. The asymmetry predicted by QED including diagrams up to order $\alpha^3$ is $A_{\mathrm{QED}} = +6.3\%$ at this angle and the prediction from the Standard Model is $A_{\mathrm{GSW}} = -11.7\%$. The total expected asymmetry to be compared to the data is then $-5.4\%$. The statistical accuracy of the measurement does not allow a distinction between the predictions of QED alone and the Standard Model. The two data points in the forward direction, corrected for QED to order $\alpha^3$, are included in Fig. 2c. The fitted asymmetry for $s = 1182\ \mathrm{GeV}^2$ changes only slightly if the two forward points are included in the fit, as indicated in Table 2.

Before we turn to the interpretation of the asymmetry in the framework of electroweak theories the

**Table 2.** Measured asymmetries $A$ obtained from fitting differential cross sections. The experimental results are compared to the Standard Model prediction at the one-loop level using parametrization II with $\sin^2\theta_w = 0.217 \pm 0.014$, $M_Z = 93.7$ GeV and $a_e a_\mu = 1$

| $s$(GeV$^2$) | $\int Ldt$(pb$^{-1}$) | $N_{\mu\mu}$ | $A$(%) $\lvert\cos\theta\rvert < 1$ | $A$(%) $\lvert\cos\theta\rvert < 0.8$ | $A^{\text{one-loop}}$(%) $\lvert\cos\theta\rvert < 0.8$ |
|---|---|---|---|---|---|
| 192 | 1.57 | 458 | $+2.7 \pm 4.9$ | $+2.4 \pm 4.3$ | $-1.2$ |
| 484 | 2.41 | 264 | $-10.6 \pm 6.4$ | $-9.3 \pm 5.6$ | $-3.0$ |
| 1,182 | 71.16 | 3,199 | $-11.70 \pm 1.84 \pm 1.0$ | $-10.30 \pm 1.62 \pm 0.9$ | $-7.6 \pm 0.7$ |
| | | (3,405 | $-11.10 \pm 1.75 \pm 1.0$[a]) | | |
| 1,798 | 17.05 | 571 | $-20.10 \pm 4.28 \pm 1.7$ | $-17.69 \pm 3.77 \pm 1.5$ | $-12.5 \pm 1.1$ |

[a] Endcap points included

systematic error of the measurement should be assessed. There are two main sources for a systematic error of the asymmetry: one is remaining background, the other could be problems in the charge determination.

Background from cosmic rays or from $e^+e^- \to e^+e^-\mu^+\mu^-$ does not have an asymmetry but would dilute any genuine effect. The contamination from $e^+e^- \to e^+e^-\mu^+\mu^-$ is less than 0.7% and the error can be neglected. Background from cosmic rays at $\sqrt{s} = 34.4$ GeV is found to be less than 0.7% and thus results in a negligible correction of $A$. Around $\sqrt{s} = 42$ GeV the contamination is 3% and was corrected for; it gave a correction of $\Delta A = -0.4\%$ with a negligible error. Events from Bhabha scattering have a strong positive forward backward asymmetry. Any contamination would therefore reduce a genuine negative asymmetry. The upper limit for Bhabha contamination at the 90% confidence level is found to be 0.5%. This would distort the asymmetry by $+0.4\%$. Finally, the background from $\tau$ pairs is expected to have the same asymmetry as muon pairs, and therefore does not cause an error.

The error of the asymmetry due to false charge assignment can be estimated, assuming the charge determination to be independent for the two tracks, by the number of muon pairs with equal charges. The fraction of like sign muon pairs is $\sim 4\%$ around $\sqrt{s} = 34$ GeV and $\sim 7\%$ around $\sqrt{s} = 42$ GeV. The probability of the charge being incorrect for both particles is therefore negligible.

In addition, however, errors in the charge determination could be caused e.g. by systematic errors of the driftchamber calibration or by a twisted geometry. These effects were studied by examining the peak positions of the $1/p$ distributions separately for both charges in both the forward and backward parts of the detector. From this study a possible systematic error in the measured asymmetry of $\pm 0.5\%$ and $\pm 1\%$ was estimated at $\sqrt{s} = 34$ and 42 GeV, respectively.

In summary, the total systematic error of the asymmetry is estimated to be $\Delta A \leqq {}^{+0.5}_{-0.9}\%$ at $\sqrt{s} = 34$ GeV and $\Delta A \leqq 1.5\%$ at $\sqrt{s} = 42$ GeV.

### Comparison of the Data to Electroweak Predictions

The asymmetry in the angular distribution of muon pairs was predicted by electroweak theories as an effect of the interference of the electromagnetic and the neutral weak amplitude. We first restrict the discussion to the Standard Model [7, 16], in which the neutral weak interaction is mediated by one neutral boson $Z^0$. The differential cross section for $e^+e^- \to \mu^+\mu^-$ in the Born approximation is given by [8]:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s} \cdot [R_{\mu\mu}(1 + \cos^2\theta) + B\cos\theta]$$

where

$$R_{\mu\mu} = 1 + 2v_e v_\mu \chi + (v_e^2 + a_e^2)(v_\mu^2 + a_\mu^2)\chi^2$$
$$B = 4a_e a_\mu \chi + 8v_e v_\mu a_e a_\mu \chi^2$$

The $v_{e,\mu}$ and $a_{e,\mu}$ are the vector and axial vector weak charges of the electron and muon respectively. In the Standard Model they are:

$$v_e = v_\mu = -1 + 4\sin^2\theta_w$$
$$a_e = a_\mu = -1$$

where $\sin^2\theta_w$ is the electroweak mixing angle. The present world average for $\sin^2\theta_w$ is $0.217 \pm 0.014$ [14] including radiative corrections. This leads to a small vector weak charge $v_e = v_\mu = -0.13$ and therefore to a negligible effect of the electroweak terms on the total cross section $R_{\mu\mu}$ (see also Fig. 3). Neglecting the width of the $Z^0$ compared to its mass, $\chi$ is given by:

$$\chi = \frac{\rho G_F M_Z^2}{8\sqrt{2}\pi\alpha} \cdot \frac{s}{s - M_Z^2} \tag{I}$$

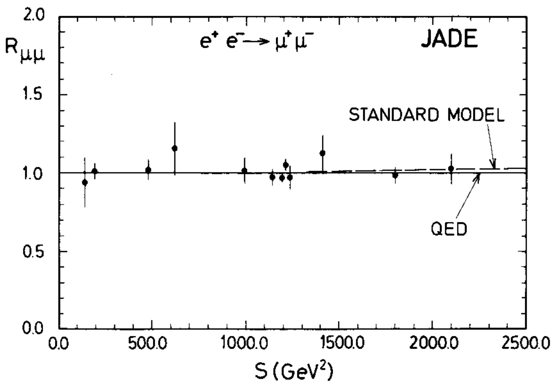


**Fig. 3.** Data for $R_{\mu\mu}$ as a function of $s$. Full line: QED prediction, dashed line electroweak prediction for $\sin^2\theta_w = 0.217$

Here, besides the mass of the $Z^0$, the Fermi coupling constant $G_F$ and $\rho = M_W^2/M_Z^2\cos^2\theta_w$ enter; $\rho$ is predicted to be 1 in the Standard Model and $M_Z = 2\sqrt{\pi\alpha/\sqrt{2}G_F}/\sin 2\theta_w$. Inserting the precisely known values for $\alpha$ and $G_F = G_\mu$ [12] and the values for $\sin^2\theta_w$ quoted above one obtains $M_Z = 90.4$ GeV. Radiative corrections increase this value to 93.8 $\pm 2.4$ GeV [14], where the error is mainly due to the error of $\sin^2\theta_w$. The parametrization (I) was traditionally used because $G_F = G_\mu$ has been measured precisely in muon decay [12]. Alternatively, one can express $\chi$ entirely by parameters from the neutral current sector of the theory, namely the electroweak mixing angle and the $Z$-boson mass [16, 17]:

$$\chi = \frac{1}{16\sin^2\theta_w\cos^2\theta_w}\,\frac{s}{s-M_Z^2} \tag{II}$$

The integrated forward-backward asymmetry is given by:

$$A = \frac{3}{2}\frac{B}{R_{\mu\mu}}\frac{c}{3+c^2}$$
$$= \frac{a_e a_\mu \chi + 2v_e v_\mu a_e a_\mu \chi^2}{1+2v_e v_\mu \chi + (v_e^2+a_e^2)(v_\mu^2+a_\mu^2)\chi^2}\cdot\frac{6c}{3+c^2}$$

where $c$ is defined as above. Neglecting the terms of order $\chi^2$ and the term $2v_e v_\mu \chi \ll 1$ in the denominator, one obtains the convenient approximation

$$A \approx a_e a_\mu \chi \cdot \frac{6c}{3+c^2}$$

which is still good to 1% at $s = 1800\ \text{GeV}^2$ in the Standard Model.

The two parametrizations of $\chi$, (I) and (II), lead to slightly different expected asymmetries in the Born approximation, if the currently best known values of the parameters are used (Table 3). This difference is roughly a factor three smaller than the present measurement errors. It disappears if the one loop corrections, which have recently been calculated by several authors, are taken into account. The corrections depend on the renormalization procedure [9, 18] and give – at present energies – a finite correction for case (I) [10] and a negligible one for (II) [6, 9, 11] (Table 3). The errors quoted

**Table 3.** Angular Asymmetries in % at the Born level ($A_B$) and at the one-loop level ($A^{\text{one-loop}}$) predicted by the Standard Model for $|\cos\theta| < 0.8$ for the two different parametrizations of $\chi$, (I) and (II).

Note: For parametrization II part of the one-loop corrections were calculated by Berends et al. [6]. Brown et al. [9] computed the missing diagrams. Combining the two results one obtains the first value for $A^{\text{one-loop}}$. Böhm et al. [11] did independently a complete calculation, which yields the second value of $A^{\text{one-loop}}$

| | | | $s = 1{,}182\ \text{GeV}^2$ | $s = 1{,}798\ \text{GeV}^2$ |
|---|---|---|---|---|
| (I) $\chi = \frac{\rho\cdot G_F\cdot M_Z^2}{8\sqrt{2}\pi\alpha}\cdot\frac{s}{s-M_Z^2}$ | Born approximation one-loop correction: | $A_B$ | −8.1 | −13.4 |
| | Wetzel [10] | $\Delta A$ | −0.6 | +1.0 |
| $a_e = a_\mu = -1$ | $A^{\text{one-loop}} = A_B + \Delta A$ | | $-7.5 \pm 0.05$ | $-12.4 \pm 0.2$ |
| $\rho = 1$ | | | | |
| $M_Z = (93.8 \pm 2.4)$ GeV | | | | |
| (II) $\chi = \frac{1}{16\sin^2\theta_w\cos^2\theta_w}\cdot\frac{s}{s-M_Z^2}$ | Born approximation one-loop corrections: | $A_B$ | −7.5 | −12.4 |
| | Berends et al. [6] | $\Delta A_1$ | $+0.6 \pm 0.2$[a] | $+1.2 \pm 0.2$[a] |
| | Brown et al. [9] | $\Delta A_2$ | −0.54 | −0.86 |
| $a_e = a_\mu = -1$ | | | | |
| $\sin^2\theta_w = 0.217 \pm 0.014$ | $A^{\text{one-loop}} = A_B + \Delta A_1 + \Delta A_2$ | | $-7.4 \pm 0.7$ | $-12.1 \pm 1.1$ |
| $M_Z = (93.8 \pm 2.4)$ GeV | | | | |
| | one-loop corrections: | | | |
| | Böhm et al. [11] | $\Delta A_3$ | −0.09 | −0.11 |
| | $A^{\text{one-loop}} = A_B + \Delta A_3$ | | $-7.6 \pm 0.7$ | $-12.5 \pm 1.1$ |

[a] Error due to finite Monte Carlo statistics

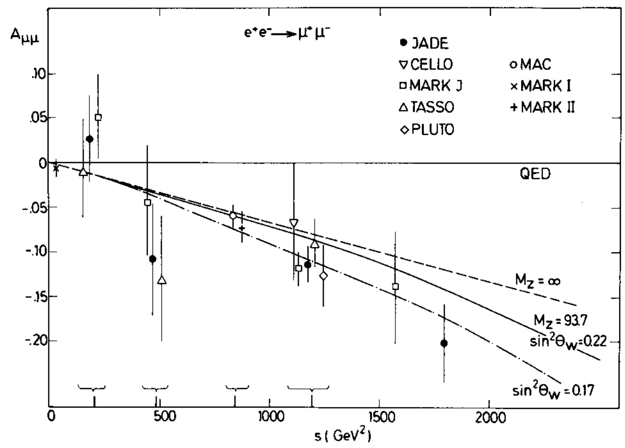


**Fig. 4.** $A_{\mu\mu}$ as a function of $s$. Data from JADE are shown together with data from SPEAR, PEP and other PETRA experiments. Note that the data taken by several detectors at the same energy were slightly displaced in $s$. The full line is the prediction of the Standard Model with $\sin^2\theta_w = 0.22$, and $M_Z = 93.7$ GeV; the dash-dotted line with $\sin^2\theta_w = 0.17$ and the same $Z$-mass

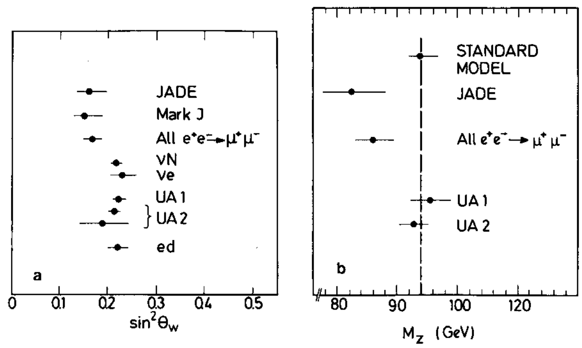


**Fig. 5. a** Measurement of $\sin^2\theta_w$ determined in $e^+e^- \to \mu^+\mu^-$ compared to other results from $\nu N$, $\nu e$, $p\bar{p}$, ed scattering. **b** Determination of the mass of the Z-boson from $e^+e^- \to \mu^+\mu^-$ compared to direct measurements from UA1 and UA2

for the final predictions in Table 3 are due to the error of $M_Z$ in case (I) and due to the errors of $M_Z$ and $\sin^2\theta_w$ in case (II). For parametrization (II) of $\chi$ the error is considerably larger.

The asymmetries expected at the one loop level from parametrization (II) are also shown in the last column of Table 2. Within the errors one finds reasonable agreement between measurement and prediction although the measured values tend to be systematically larger than those predicted.

In Figs. 3 and 4 the JADE data for $R_{\mu\mu}$ and $A$ (for $|\cos\theta| < 1$) are shown together with QED and electroweak predictions as a function of $s$. In Fig. 4 in addition to the JADE asymmetries, results from other PETRA detectors [3] and from SPEAR and PEP [4] at lower energies are also shown. The measurements at all values of $s$ are within one or two standard deviations from the prediction of the Standard Model with $\sin^2\theta_w = 0.22$ (corresponding to $M_Z = 93.8$ GeV). However all the data at high energy have a larger asymmetry than predicted. Averaging the PETRA data one gets $-(11.0 \pm 1.1)\%$ at $s \sim 1190\ \mathrm{GeV}^2$ and $-(17.8 \pm 3.7)\%$ at $s \sim 1726\ \mathrm{GeV}^2$. These values are by 2 and 1 standard deviations larger than the theoretical expectations of $-8.6\%$ and $-13.5\%$ respectively.

A combined fit to the total cross section and the forward-backward asymmetry using parametrization (I) with $M_Z = 93.8 \pm 2.4$ GeV fixed, was performed. Assuming $\rho = 1$ one obtains $a_e a_\mu = 1.15 \pm 0.08$ for the JADE data alone and $a_e a_\mu = 1.10 \pm 0.04$ for all data. This is in agreement with the prediction of the Standard Model, $a_e a_\mu = 1$, and in conjunction with measurements of $a_e$ from $\nu_e$ scattering confirms $e - \mu$ universality. Alternatively one can get constraints on $\rho$ if $a_e a_\mu = 1$ is fixed, $\rho = 1.34 \pm 0.16$ and $\rho = 1.20 \pm 0.09$ for the JADE data and all data respectively.

In parametrization (I) of $\chi$ $A$ is rather insensitive to $M_Z$ or $\sin^2\theta_w$. In parametrization (II) however, $\sin^2\theta_w$ and $M_Z$ are free parameters and the sensitivity to $\sin^2\theta_w$ improves if $M_Z$ can be fixed. The $Z$ mass has recently been measured at the $p\bar{p}$ collider [13], by the UA1 and UA2 collaborations. Their results average to $M_Z = 93.7 \pm 2$ GeV. Using this mass and assuming $a_e a_\mu = 1$ one obtains:

$\sin^2\theta_w = 0.16 \pm 0.03$ for the JADE data;

and

$\sin^2\theta_w = 0.17 \pm 0.02$ for all data.

In Fig. 4, a curve for $A$ as a function of $s$ using this fitted value of $\sin^2\theta_w$ is also shown.

The JADE value of $\sin^2\theta_w$ agrees well with the MARK J result obtained previously in a similar way [3, 17]. The values for $\sin^2\theta_w$ derived from $e^+e^- \to \mu^+\mu^-$ are shown in Fig. 5a together with results from other processes. The $e^+e^-$ result agrees within 2 standard deviations with the value from $\nu N$ scattering, which has the smallest errors.

One can also obtain good constraints on the $Z$ mass leaving $\sin^2\theta_w$ fixed: $M_Z = (82^{+6}_{-4})$ GeV for the JADE data and for all data $M_Z = 86 \pm 3$ GeV. This indirect method yields values which are in agreement with the results from the UA1 and UA2 experiments as shown in Fig. 5b.

In summary, a study of the reaction $e^+e^- \to \mu^+\mu^-$ using the JADE - detector at PETRA yields the following results: The integrated cross section is well described by QED up to order $\alpha^3$ for cm energies between 14 and 46 GeV. At high energies $\langle\sqrt{s}\rangle = 34.4$ GeV and $\langle\sqrt{s}\rangle = 42.4$ GeV, the angular distributions show forward-backward charge asymmetries of $A = -(11.70 \pm 1.84 \pm 1.0)\%$ and $A = -(20.1 \pm 4.3 \pm 1.7)\%$, respectively. The asymmetries, although in agreement with the predictions of the Standard Model, ($-8.6\%$ and $-14.2\%$ using $\sin^2\theta_W = 0.217$ and $M_Z = 93.8$ GeV) are both slightly larger. This small deviation is confirmed by the measurements of the other PETRA detectors at high energies. Combining the PETRA data, the measured asymmetries are higher than the predictions by 2 and 1 standard deviation around $\sqrt{s} \sim 34.5$ GeV and $\sqrt{s} \sim 41.5$ GeV, respectively. This is reflected in similar deviations from the expectation when fitting the electroweak parameters $a_e a_\mu$, $\rho$ and $\sin^2\theta_W$. These parameters were determined for the JADE data alone and also using all published data from experiments at SPEAR, PEP and PETRA.

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## References

1. JADE Collab. W. Bartel et al.: Phys. Lett. **88B**, 171 (1979); H. Drumm et al.: Wire Chamber Conf. 1980, p. 333. Eds. W. Bartl, M. Regler, Amsterdam: North Holland
2. JADE Collab. W. Bartel et al.: Phys. Lett. **108B**, 140 (1982); JADE Collab. W. Bartel et al.: Phys. Lett. **99B**, 281 (1981)
3. CELLO Collab. H.J. Behrend et al.: Z. Phys. C – Particles and Fields **14**, 283 (1982); MARK J Collab. B. Adeva et al.: Phys. Rev. Lett **48**, 1701 (1982); MIT-LNS Report No. 131 (1983) subm. to Phys. Rep.; PLUTO Collab. Ch. Berger et al.: Z. Phys. C – Particles and Fields **21**, 53 (1983); TASSO Collab. M. Althoff et al.: Z. Phys. C – Particles and Fields **22**, 13 (1984)
4. MARK I Collab. T. Himel et al.: Phys. Rev. Lett. **41**, 449 (1978); MARK II Collab. M.E. Levi et al.: Phys. Rev. Lett. **51**, 1941 (1983); MAC Collab. E. Fernandez et al.: Phys. Rev. Lett. **50**, 1238 (1983); SLAC Preprint SLAC-PUB-3133 (1983)
5. F.A. Berends et al.: Nucl. Phys. **B63**, 381 (1973); F.A. Berends et al.: Nucl. Phys. **B177**, 237 (1981); F.A. Berends, R. Kleiss: DESY-Report 80-66 (1980)
6. F.A. Berends, R. Kleiss, S. Jadach: Nucl. Phys. **B202**, 63 (1982)
7. S.L. Glashow: Nucl. Phys. **22**, 579 (1961); Rev. Mod. Phys. **52**, 539 (1980); A. Salam: Phys. Rev. **127**, 331 (1962); Rev. Mod. Phys. **52**, 525 (1980); S. Weinberg: Phys. Rev. Lett. **19**, 1264 (1967); Rev. Mod. Phys. **52**, 515 (1980)
8. R. Budny: Phys. Lett. **55B**, 227 (1975)
9. R.W. Brown, K. Decker, E.A. Paschos: Phys. Rev. Lett. **52**, 1192 (1984)
10. W. Wetzel: Nucl. Phys. **B227**, 1 (1983); Preprint Heidelberg, May 1983
11. M. Böhm, W. Hollik: Nucl. Phys. **B204**, 45 (1982), DESY 83-060/83-118; Z. Phys. C – Particles and Fields **23**, 31 (1984)
12. Particle Data Group M. Roos et al.: Phys. Lett. **111B** (1982)
13. G. Arnison et al.: Phys. Lett. **126B**, 398 (1983); Phys. Lett. **129B**, 273 (1983); P. Bagnaia et al.: Phys. Lett. **129**, 130 (1983); Z. Phys. C – Particles and Fields
14. A. Sirlin, W.J. Marciano: Nucl. Phys. **B189**, 442 (1981); C. Llewellyn-Smith, J. Wheater: Phys. Lett. **105B**, 486 (1981); W.J. Marciano in p. 80: 1983 Int. Symposium on Lepton and Photon Interactions at High Energies, Cornell University, Ed. D.G. Cassel, D.L. Kreinick 1983
15. W. Krenz: Compilation of Neutrino Electron Scattering Data and Remarks on Lepton Coupling Constants, University Aachen Preprint, PITHA 82/26
16. A recent theoretical survey of the Standard Model and references are given in L.M. Sehgal: Neutral Currents, Theory and Application, University Aachen Preprint, PITHA 84/03, to be published in Prog. Part. Nucl. Physics
17. A. Böhm: Measurement of $\sin^2\theta_w$ from the Reaction $e^+e^- \to \mu^+\mu^-$, University Aachen Preprint, PITHA 84/11; A. Böhm: Testing the Standard Model: A Summary of the Moriond Conference, University of Aachen Preprint, PITHA 84/13
18. M. Böhm, H. Spiesberger, W. Hollik: The Renormalization of the Standard Model, DESY 84-027

**Note added in proof**

Recently the HRS group at PEP also published a measurement of the electroweak asymmetry at $\sqrt{s} = 29$ GeV (D. Bender et al.: Phys. Rev. **D30**, 515 (1984)). Their results are in agreement with the values expected within the Standard Model.