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Final results on muon and tau pair production by the JADE Collaboration at PETRA

JADE Collaboration

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Abstract. The cross-sections and the forward-backward charge asymmetries of muon and tau pairs produced in e^+e^- collisions at $\sqrt{s}=35$ GeV have been measured by the JADE Collaboration. The cross-sections, $\sigma_\mu(\sqrt{s}=35\text{ GeV})=69.79\pm1.35\pm1.40$ pb and $\sigma_\tau(\sqrt{s}=35\text{ GeV})=71.72\pm1.48\pm1.61$ pb, are in agreement with the QED α^3 prediction. The charge asymmetries are $A_\mu=-(9.9\pm1.5\pm0.5)$% and $A_\tau=-(8.1\pm2.0\pm0.6)$% in agreement with the value -9.2% predicted by the standard model, using $M_Z=91.0$ GeV and $\sin^2\theta_W=0.230$.

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Introduction

The production of muon pairs is one of the simplest reactions in which the predictions of QED and the standard model [1] can be tested in e^+e^- annihilations. Whereas QED – in lowest order – predicts a symmetric angular distribution for the muon pairs the standard model predicts an asymmetry at PETRA energies, $\sqrt{s}\approx30$ GeV. This asymmetry is due to the interference of the photon and the Z^0 amplitudes. The magnitude of the asymmetry depends on the center-of-mass energy and on the values of the parameters of the model.

The asymmetry was first established experimentally when the e^+e^- storage ring PETRA was operating at center-of-mass energies of $\sqrt{s}\approx34$ GeV [2, 3]. Since that time numerous measurements of the angular asymmetry of muon pairs have been made by experiments at PEP ($\sqrt{s}=29$ GeV), PETRA ($\sqrt{s}\approx30$–45 GeV) and recently also TRISTAN ($\sqrt{s}$ up to ≈60 GeV) [23]. In addition the asymmetry was also measured for the process $e^+e^-\to\tau^+\tau^-$, which, according to the standard model, should be identical to that of $e^+e^-\to\mu^+\mu^-$. The magnitude of the asymmetry was in general found to agree with the numerical predictions of the standard model within experimental errors [4]. However it was noticed that the magnitude of the measured muon asymmetries at an energy of $\sqrt{s} \approx 34$ GeV were approximately two standard deviations above the expectation. For $e^+e^- \to \tau^+\tau^-$ the opposite was true: although in agreement with the theory, albeit with somewhat larger errors, almost all measurements were below the expectation. This has sometimes been attributed to unrecognised background in the tau pair data samples.

No deviation from the QED prediction could be found in the total cross-sections of muon and tau pairs in the PEP and PETRA energy range. This is as expected in the standard model since the predicted deviations from pure QED, with the given parameter values, are below the experimental errors.

Here we present the results of an analysis of data which were accumulated with the JADE detector in the last year of operation of the e^+e^- storage ring PETRA. Data were taken at $\sqrt{s} = 35$ GeV and 4772 muon pairs corresponding to an integrated luminosity of 88.3 pb^{-1} and 3238 tau pairs corresponding to 92.5 pb^{-1} were analysed. In the muon pair analysis a renewed effort was made to understand the absolute normalisation. As a further test of the predictions of the standard model the angular asymmetry was studied as a function of the acollinearity of the muon pairs. In the tau-pair analysis the main point of interest was an improved determination of background, in particular of any contamination by events from Bhabha scattering.

Detector

The upgraded JADE detector [5, 6] was used for the measurement. The tracking system consisted of three detectors, the jet-chamber, a vertex detector close to the beam interaction region and a z-chamber surrounding the jet-chamber. The heart of the detector was the jet-chamber with the new flash-ADC electronics which resulted in an improved resolution of 110 μm in the drift direction ($r\varphi$) and a double track resolution of better than 2 mm. The longitudinal z-coordinate was measured by charge division in the jet-chamber and in addition an accurate point was delivered by the z-chamber at a radius of ~ 1 m. The latter had a precision of better than 0.5 mm and led to an overall z-resolution in combination with the jet-chamber of ~ 20 mrad in the polar angle θ.

Another improvement of the detector was the installation of a vertex detector inside the jet-chamber close to the interaction point. Its main purpose was to increase the accuracy of life-time measurements, but it had the side effect of further improving the momentum resolution and improving the rejection of background for the tau pair analysis. The momentum resolution for high momentum tracks was determined to be $\Delta p/p^2 \approx 1.0\%\ \text{GeV}^{-1}$, which is reflected as a full width at half maximum of $\approx 40\%$ in Fig. 1. The electromagnetic shower detector consisted of lead-glass blocks, the majority of which were SF5 with a radial length of $12 X_0$.

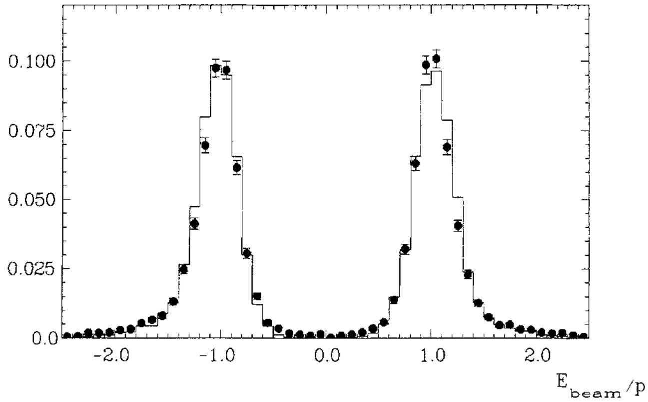

Fig. 1. Distribution of E_{beam}/p for muon pair candidates, $E_{\text{beam}} = 17.5$ GeV. The histogram shows the results of the simulation

For the running at PETRA's highest energies the middle part of the barrel ($|\cos\theta| < 0.277$) was replaced by SF6 of $18 X_0$ depth, thus diminishing energy leakage. The energy resolution was $\sigma_E/E = 0.04/\sqrt{E} + 0.015$ (E in GeV); the angular resolution for electrons at high energies was $\sigma_\phi = 10$ mrad and $\sigma_\theta = 12$ mrad.

The detector was surrounded by the muon filter which was designed to detect penetrating particles. It consisted of layers of absorbers interleaved by drift-chambers and was unchanged compared to previous analyses. A particle moving from the interaction point through the muon filter perpendicular to the beams had to traverse a minimum of 6.4 absorption lengths.

μ-Pairs

The selection of muon and tau pairs followed the same procedure as described in previous publications [2, 7, 8]. It is only briefly summarized here. Muon pairs were selected by demanding two high momentum tracks which came from the interaction region and which left a pattern in the muon filter corresponding to minimum ionizing particles. The time of flight of the muon candidates had to agree with the beam timing thus eliminating cosmic rays. Contrary to previous selections no cut was made on the acollinearity angle. In practice it was restricted by the acceptance cut which demanded that both

Table 1. Determination of the total cross-sections for $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$. σ_0 is the radiatively corrected measurement and σ_{QED} the QED prediction in lowest order

	$e^+e^- \to \mu^+\mu^-$	$e^+e^- \to \tau^+\tau^-$
Events	4772	3238
Background (%)	2.66 ±0.31	5.75 ±0.46
Losses (%)	15.50 ±0.83	15.40 ±0.70
$L(\text{pb}^{-1})$	88.33 ±0.29	92.49 ±0.30
Acceptance (%)	68.10 ±0.40	40.87 ±0.39
Rad. Corr. (α^3)	1.306 ±0.001	1.311 ±0.009
σ_0 (pb)	69.79 ±1.35	71.72 ±1.48
σ_{QED} (pb)	70.9	70.9
$R = \sigma_0/\sigma_{\text{QED}}$	0.984 ±0.019	1.012 ±0.021

muon candidates have $|\cos\theta|<0.85$. Background from the reaction $e^+e^-\to e^+e^-\mu^+\mu^-$, giving in general a muon pair of lower momenta, and tau pairs were eliminated by a cut on the momentum sum of the muon tracks. The cut varied with the acollinearity angle. The remaining background was estimated to amount to 2.7%. The background fraction is reduced to 0.94% if an acollinearity cut of 200 mrad is applied as in previous publications.

The acceptance was studied using a Monte Carlo simulation of $e^+e^-\to\mu^+\mu^-$ to order α^3 by Berends et al. [9]. The detector effects – resolutions, efficiencies, etc. – were then simulated for the particles and the same cuts applied as in the data. The geometrical detector acceptance defined by $|\cos\theta|<0.85$ is 73.4%; it is reduced to 68.1% by the cuts on track quality and by the efficiency of the muon identification. Additional losses – not included in the simulation – were caused by the trigger inefficiency (4.5%), inefficiencies of the time-of-flight counters (5.2%), and losses due to calibration errors (5.8%). The losses were determined using appropriate data samples, e.g. the trigger and counter inefficiencies were determined using tau pair data which were triggered by independent triggers based on the shower counters. The losses due to calibration errors were determined by reprocessing a fraction of the data with the final calibrations.

After correcting for α^3 contributions from QED the total measured cross-section is:

$$\sigma_\mu(\sqrt{s}=35\ \text{GeV})=69.79\pm1.35\pm1.40\ \text{pb}$$

where the first error is statistical and the second contains the estimated systematic uncertainties from the luminosity measurement, the acceptance calculation and the background determination. This measurement can be directly compared with the QED prediction in lowest order for $\sqrt{s}=35$ GeV which is 70.9 pb. The new measurement agrees well with this theoretical prediction. The deviation from pure QED predicted by the standard model is $+0.2$ pb with present parameter values (for the numbers see paragraph on comparison with the standard model), which is too small to be detected given the experimental errors.

For the calculation of the differential cross-section the events were split in 10 bins of $\cos\theta$, where θ was the polar angle of the μ^+ with respect to the flight direction of the positron. The corrections for event losses and background were applied as for the calculation of the total cross-section; they have no angular asymmetry. Radiative corrections for α^3 effects from pure QED were applied, they have an asymmetry of about $+1.5\%$ in the accepted angular range. The corrected cross-section is shown in Fig. 2a. It is well described by a function of the form predicted by the standard model: $s\,d\sigma/d\Omega\propto 1+\cos^2\theta+8/3\,A\cos\theta$. The parameter A is the integrated angular asymmetry, which is defined as $A=\frac{N_F-N_B}{N_F+N_B}$, where N_F denotes the number of "forward" and N_B the number of "backward" events, respectively.

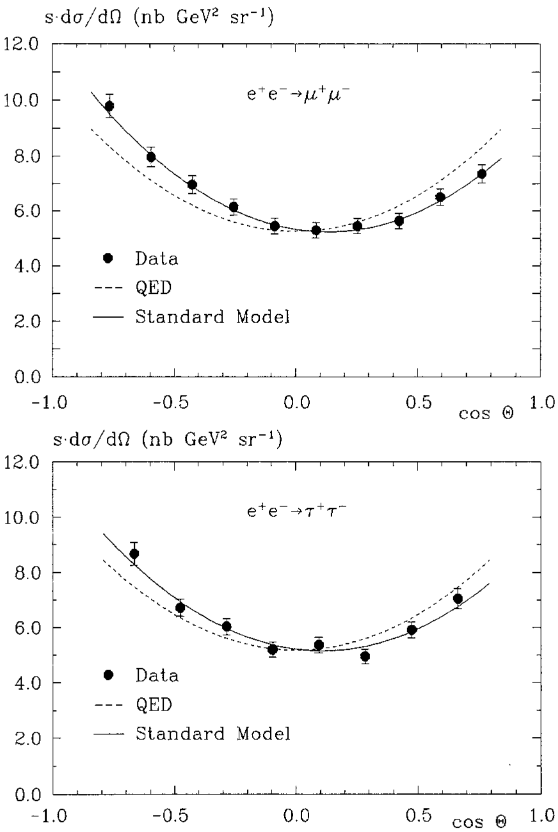

Fig. 2a, b. Differential Cross-Section for **a)** $e^+e^-\to\mu^+\mu^-$ and **b)** $e^+e^-\to\tau^+\tau^-$ at $\sqrt{s}=35$ GeV after QED radiative corrections. The full lines represent 2-parameter fits to the form $N(1+\cos^2\theta+8/3\,A\cos\theta)$ (the numerical results for A are given in the text) while the dotted lines are symmetric QED predictions

Events are counted as forward (backward) if the angle of the positive muon with respect to the positron beam direction is smaller (larger) than 90°. The fit to the data shown in Fig. 2a yields the asymmetry:

$$A_\mu=-0.099\pm0.015\pm0.005.$$

Restricting the data sample to an acollinearity of ≤ 200 mrad as in previous analyses the result remains unchanged within the errors.

The new value for A_μ agrees well with our previous statistically independent result of $-0.111\pm0.018\pm0.010$ at an energy of $\langle\sqrt{s}\rangle=34.4$ GeV [7]. We have given a smaller estimate of the systematic error which results mainly from our better understanding of the charge determination and the background.

In lowest order electroweak theory muon pairs are produced back to back, i.e. within experimental resolution they are collinear. Emission of hard photons either in the initial or the final state leads to acollinear muon pairs. The acollinearity distribution of the selected events is shown in Fig. 3; it is well described by the standard simulation, which includes α^3 effects.

The muon asymmetry was also studied as a function of acollinearity, see Fig. 4. The theoretical expectation can be interpreted as follows. In pure QED collinear

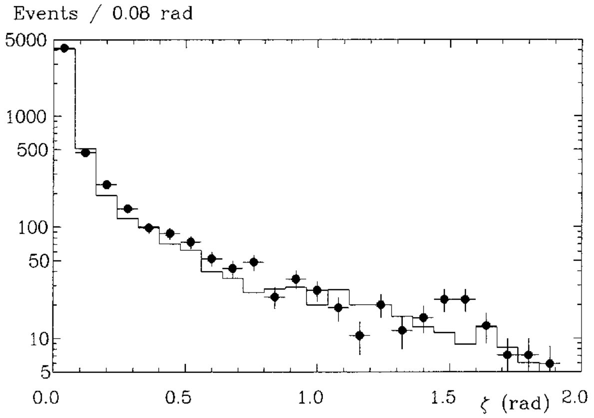

Fig. 3. Acollinearity distribution of muon pair candidates. The histogram shows the simulation including α^3 contributions

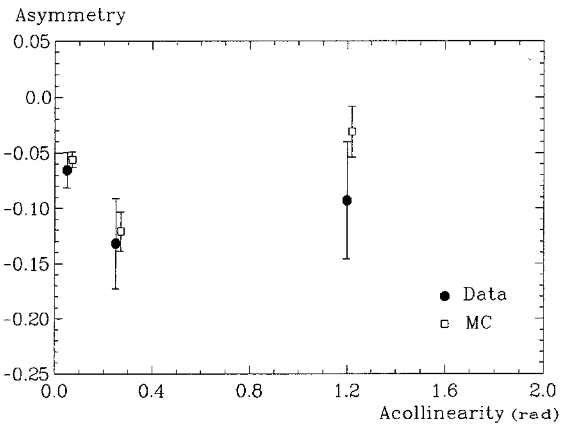

Fig. 4. Asymmetry for $e^+e^- \to \mu^+\mu^-$ as a function of acollinearity for data and Monte Carlo simulation. The simulation includes electroweak contributions and full α^3 radiative corrections. The parameters are as in the text, except M_Z which was set to 91.9 GeV

events have a positive asymmetry due to the interference of two photon exchange processes with one photon exchange. Non-collinear events on the other hand have a negative asymmetry due to the interference of amplitudes with photon emission in the initial and final states. The interference with the Z-amplitude shifts the whole curve to negative values. Due to the finite angular resolution the abrupt change of the asymmetry to negative values when allowing for an acollinearity is smeared out.

The data were split into three acollinearity bins and the asymmetries in these bins were computed by comparing the number of events in the forward and backward directions. In Fig. 4 the results are compared with the prediction of a Monte Carlo computation including α^3 effects, i.e. photonic corrections for photon and for Z^0 exchange diagrams. It can be seen that the agreement between data and simulation is good. Previously, in an independent analysis the fraction of acollinear events with a visible energetic photon has been shown to agree with the standard model in separate studies for both $\mu^+\mu^-\gamma$ and for $\tau^+\tau^-\gamma$ [10].

τ-Pairs

The tau selection, described in detail in [8], was designed to select all decays except those where both taus decayed into electrons or muons plus neutrinos. These latter events were excluded because of the overwhelming background from $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to e^+e^-$. The event selection started with a topology requirement: all charged and neutral particles had to lie in two opposite cones of half opening angle 45°. The angle between the cone axes was restricted to values below 100° and the polar angle of both cone axes was required to have $|\cos\theta| < 0.76$. Cuts were applied to reject background from $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to$ hadrons and two photon production of muons, taus and hadrons. Particular care was taken to reject events from Bhabha scattering, the main cuts were the following: events were eliminated if they had a total shower energy above $0.80\sqrt{s}$, or a single shower above $0.45\sqrt{s}$, or in which the charged particles deposited shower energies of more than $0.60\sqrt{s}$. Finally events were rejected if they only contained two electrons in the two hemispheres. Electrons were recognized by comparing the energy deposited in the lead-glass counters with the particle momentum. All events were then subjected to a visual scan in order to eliminate as much of the remaining background as possible.

The background from Bhabha events was carefully analysed since it has a particularly strong impact on the asymmetry measurement. In the acceptance region the Bhabha cross-section to order α^3 is a factor 17.5 higher than the tau pair cross-section and the asymmetry is $\approx +78\%$ due to the presence of the t-channel photon exchange. After the energy cuts mentioned above, Bhabha events are in general only accepted as tau candidates for two reasons: either they radiate a large amount of their energy, the radiated photons remain undetected and the electrons are not recognised as such; or they can be accepted due to detector deficiencies like defective lead-glass channels or gaps between the lead-glass counters.

For the simulation of the Bhabha background a Monte Carlo program was used which, in addition to complete α^3 effects [11], simulated higher orders approximately by radiating multiple photons in the final state [12, 13]. In addition, the gaps between the lead-glass blocks which in total amount to roughly 2% of the inner surface of the lead glass array were simulated. An electron hitting such a gap can escape without depositing an appreciable amount of energy. The general detector simulation program GEANT [14] was used leading to a background estimate of $(2.7 \pm 0.4)\%$. A large fraction of these events was however rejected in the visual scan which was tailored to reject Bhabha scattering candidates by explicitly removing events where a track opposite to a showering particle pointed to a counter gap or a defective channel. Thus the final background in the data sample from Bhabha scattering was estimated to be $(1.2 \pm 0.3)\%$. This estimate is higher than our previous result which was $(0.6 \pm 0.6)\%$. The two estimates are however compatible within the errors.

Additional background came from two photon production of tau pairs (2.0%), other two photon processes (1.4%), multihadronic events (0.86%) and muon pairs (0.4%).

Event losses were mainly due to nuclear interactions (3.7%), the visual scan (9.8%) and small losses due to cuts (1.9%). The comparitively high loss of events in the visual scan resulted from the scanners' aim of obtaining a clean sample of tau events for the determination of the tau lifetime. The loss was determined by analysing in detail the scanners' criteria for rejecting events.

The acceptance was calculated using a Monte-Carlo event generator incorporating α^3 effects [9]. The tau decay branching ratios were taken from [15]; they were however adjusted to sum up to 100% and to reproduce well the measured topological branching ratios. Due to the event selection the acceptance is not very sensitive to the branching ratios, their uncertainties lead to an acceptance error of 0.7%. The detector effects were taken into account and the same cuts applied as for the data. The measured cross-section after correcting for α^3 effects is

$$\sigma_\tau(\sqrt{s}=35\text{ GeV})=71.72\pm1.48\pm1.61\text{ pb}.$$

The systematic error is due to errors in the luminosity determination, the radiative corrections, the acceptance calculation and the determination of background and event losses. The agreement with the theoretical prediction of 70.9 pb and our previous measurements [8] is good.

In order to determine the differential cross-section only those events were selected in which at least one hemisphere of the event contained exactly one good track. Its charge was then used to determine whether the event was forward or backward. The polar angle of the tau was approximated by the polar angle of the vector difference of the two momentum vectors of the event hemispheres which were calculated by summing the charged and neutral particle momenta. The differential cross-section corrected for background and α^3 QED effects for the 2932 accepted events is shown in Fig. 2b; the asymmetry due to α^3 QED effects was +1.3%. The remaining asymmetry was calculated from a fit to the measured differental cross-section as for muon pairs. The result is:

$$A_\tau=-0.081\pm0.020\pm0.006.$$

The systematic error contains contributions from uncertainties in radiative corrections the determination of the "positive" tau direction, and from the background determination (mainly Bhabha scattering). To check that this result was not influenced by remaining background from Bhabha scattering, the asymmetry was determined using only non showering events and also event samples in which events pointing to counter gaps had been removed. No significant change was observed in the resulting asymmetry.

The corresponding measurement at $\sqrt{s}=34.6$ GeV was $A_\tau=-0.060\pm0.025\pm0.010$ [8] which becomes −0.067 if the present estimate of Bhabha background is also applied to the old data. The new measurement is in agreement with the old one. For convenience all JADE lepton asymmetry measurements are given in Table 2 and Fig. 5.

Table 2. Asymmetries for $e^+e^-\to\mu^+\mu^-$ and $\tau^+\tau^-$. If two errors are given, the second one is due to systematic errors

$e^+e^-\to\mu^+\mu^-$

$\sqrt{s}$ (GeV)	$\int Ldt$ (pb^{-1})	Events	A (%)	A_{SM}[a] %
13.9	1.6	458	+ 2.7±4.9	− 1.2
22.0	2.4	264	−10.6±6.4	− 3.3
34.4	71.2	3400	−11.1±1.8±1.0	− 8.8
35.0	88.3	4772	− 9.9±1.5±0.5	− 9.2
38.0	11.9	422	− 9.7±5.0±1.0	−11.2
43.7	43.1	1258	−19.1±2.8±1.0	−15.9

$e^+e^-\to\tau^+\tau^-$

$\sqrt{s}$ (GeV)	$\int Ldt$ (pb^{-1})	Events	A (%)	A_{SM}[a] (%)
34.6	62.4	1998	− 6.7±2.5±1.0[b]	− 8.9
35.0	92.5	2935	− 8.1±2.0±0.6	− 9.2
38.0	11.8	336	+ 6.8±6.3±1.0[b]	−11.2
43.7	43.1	913	−17.7±3.6±1.0[b]	−15.9

[a] A_{SM} was computed with the formula given in the text with $M_Z=91.0$ GeV and $\sin^2\theta_W=0.230$

[b] Modified compared to the old publications to take into account the increased estimate of Bhabha background

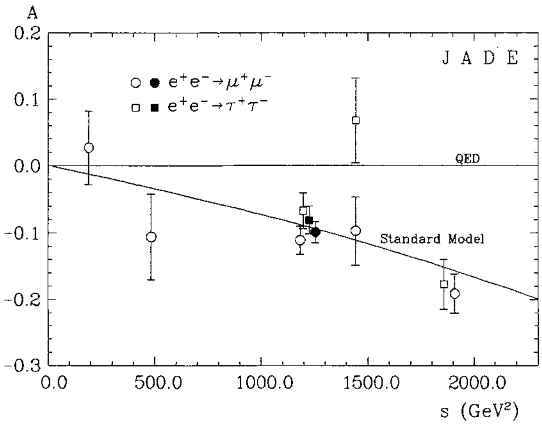

Fig. 5. Asymmetry for $e^+e^-\to\mu^+\mu^-$ and $e^+e^-\to\tau^+\tau^-$ as a function of s. The new data are shown as full points, the error bars include statistical and systematic errors added in quadrature. The curves show the predicted asymmetry in lowest order for QED and the Standard Model with $\sin^2\theta_W=0.230$ and $M_Z=91.0$ GeV

Comparison with the Standard Model

According to the prediction of universality of generations, which is also built into the standard model, the asymmetries of muon and tau should be equal. The new measurements support this; the direct comparison of the present muon and tau asymmetries yields:

Table 3. Summary of axial coupling constants

JADE

	$\sqrt{s}\approx 34.7$ GeV			$\sqrt{s}\approx 30$–46 GeV
	1986	pre-1986	combined	
a_μ	1.08 ± 0.17	1.27 ± 0.23	1.15 ± 0.14	1.16 ± 0.10
a_τ	0.88 ± 0.23	0.75 ± 0.30	0.84 ± 0.18	0.90 ± 0.14
a_μ/a_τ	1.22 ± 0.37	1.68 ± 0.73	1.37 ± 0.34	1.28 ± 0.23

PETRA (CELLO, JADE, MARK J, PLUTO, TASSO)

	$\sqrt{s}\approx 34.7$ GeV			$\sqrt{s}\approx 30$–46 GeV
	1986	pre-1986	combined	
a_μ	1.04 ± 0.11	1.25 ± 0.12	1.13 ± 0.08	1.12 ± 0.06
a_τ	0.88 ± 0.15	0.82 ± 0.21	0.86 ± 0.12	0.90 ± 0.09
a_μ/a_τ	1.17 ± 0.23	1.52 ± 0.41	1.32 ± 0.21	1.26 ± 0.15

$$\frac{A_\mu}{A_\tau}=1.22\pm 0.37$$

including statistical and systematic errors which were added in quadrature.

In order to increase the significance of this comparison our older independent results were included and – in a second step – also the results of the other PETRA experiments. Since these data were obtained at different energies they were compared to the prediction of the standard model, which is in lowest order:

$$A=\frac{3}{8}\,\frac{4a_e\,a_{\mu(\tau)}\,\chi+8\,v_{\mu(\tau)}\,a_{\mu(\tau)}\,a_e\,v_e\,\chi^2}{1+2v_{\mu(\tau)}\,v_e\,\chi+(v_e^2+a_e^2)(v_{\mu(\tau)}^2+a_{\mu(\tau)}^2)\,\chi^2}$$

where

$$\chi=\frac{1}{16\sin^2\theta_W\cdot\cos^2\theta_W}\cdot\frac{s}{s-M_Z^2}.$$

Using $\sin^2\theta_W=0.230$ [16] and $M_Z=91.0$ GeV [17] and standard couplings, i.e. $a_e=a_{\mu(\tau)}=-1$ and $v_e=v_{\mu(\tau)}=-1+4\sin^2\theta_W$, the predicted asymmetry at $\sqrt{s}=35$ GeV is calculated to be -9.2%. In the above parameterisation the theoretical asymmetry can be directly compared with the data in Table 2 and this comparison is correct up to the one loop level*.

Using the measured asymmetry values the axial coupling constant of the muon or tau were determined from the theoretical expression. The averaged results for $a_{\mu(\tau)}$ and for the ratio a_μ/a_τ are given in Table 3 for the JADE data as are the results obtained when all PETRA data are used [20]. The errors in the table contain statistical and systematic contributions from the asymmetry measurement. An additional uncertainty comes from the error of the Z-mass and $\sin^2\theta_W$. An uncertainty of ± 0.1 GeV in the Z-mass – this is the present error estimate for the direct mass measurements [17] – leads to an uncertainty of ± 0.003 in the coupling constants, an uncertainty of ± 0.005 in $\sin^2\theta_W$ to an uncertainty of ± 0.015 in the mu or tau coupling constants. Both errors are negligible compared with the experimental errors of the asymmetry measurements and are not contained in the table.

The "new" measurements at $\sqrt{s}=35$ GeV are shown in column 2 of Table 3 and the "old" ones at a similar energy in column 3 in the same table (note that the numbers in this column have been re-calculated using the new Z-mass and $\sin^2\theta_W$). The comparison shows better agreement with the universality prediction for the new data, not only for JADE data, but also for the results using all PETRA data. The best statistical accuracy is obtained when all data at all energies are used. The trend that a_μ is slightly higher and a_τ lower than expected is still observed: $a_\mu/a_\tau=1.26\pm 0.15$. The deviation from 1 in a_μ/a_τ corresponds to 1.7 standard deviations. This number does not change significantly if the data from the PEP collaborations are included [21].

* For a discussion of radiative corrections for different parameterisations see e.g. [7, 18, 19]

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