MEASUREMENT OF THE REACTION $e^+e^- \to \tau^+\tau^-$ AT $\sqrt{s} = 29$ GeV

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The reaction $e^+e^- \to \tau^+\tau^-$ has been measured using the high resolution spectrometer at PEP. The angular distribution shows a forward–backward asymmetry of $-(6.1 \pm 2.3 \pm 0.5)\%$, corresponding to an axial-vector coupling $g_a^\tau g_a^e = 0.28 \pm 0.11 \pm 0.03$, in good agreement with the standard model of electroweak interactions. The measured cross section yields $R_{\tau\tau} = 1.10 \pm 0.03 \pm 0.04$, consistent with QED and giving QED cutoff parameters of $\Lambda_+ > 92$ GeV and $\Lambda_- > 246$ GeV at 95% C.L.

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The $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$ reactions provide a clean test of the Glashow–Weinberg–Salam theory [1] of the electroweak interaction. A forward–backward asymmetry has been measured in the $\mu^+\mu^-$ final state [2]; however, because of the lower detection efficiency, the electroweak interference in $e^+e^- \to \tau^+\tau^-$ is still not well measured. In this letter we present new data on the reaction $e^+e^- \to \tau^+\tau^-$ at $\sqrt{s} = 29$ GeV using the high resolution spectrometer (HRS) at PEP. The results are based on an integrated luminosity of 106 pb^{-1}.

The HRS detector has been described in detail elsewhere [3]. Features of the detector relevant for this analysis include charged-particle tracking over 90% of the solid angle in a solenoidal magnetic field of 16.2 kG, and measurement of electromagnetic shower energy with lead-scintillator calorimeters covering the angular intervals $|\cos\theta| < 0.60$ (barrel) and $0.70 < |\cos\theta| < 0.96$ (endcap), where θ is the angle with respect to the beam direction. The momentum resolution for high momentum tracks at large angles is $\sigma_p/p \simeq 2 \times 10^{-3} \cdot p$ (p in GeV/c). The charge is unambiguously identified for $|\cos\theta| < 0.90$. The 40 module barrel shower counter system has an energy resolution of $\sigma_E/E = 16\%/\sqrt{E}$ (E in GeV) and a time of flight resolution of $\sigma = 360$ ps. The energy resolution for the 40 module endcap system is $\sigma_E/E = 20\%/\sqrt{E}$.

The τ-pair production of $\sqrt{s} = 29$ GeV yields a final state with a clear back to back topology, allowing the events to be selected with little background. We restrict this analysis to cases in which the τ decays to one or three charged particles. In order to select the events with good efficiency, to limit detector biases, and to discriminate against backgrounds, all of the events were required to satisfy the following selection criteria: Each event had zero net charge and contained 2, 4 or 6 tracks, with 1 or 3 tracks in each hemisphere. The distance of closest approach of a track to the interaction point was less than 1 cm radially and less than 9 cm along the beam direction. The scalar sum of the charged momenta was between 7.25 GeV/c and 23.2 GeV/c. The background from Bhabha scattering was reduced by requiring that the total momentum of any jet to be less than 13 GeV/c. Two photon contamination was minimized by requiring that the acollinearity angle between the two jets to be less than 45°.

Additional selection criteria were applied separately to the two-prong, and to the four- and six-prong events. For two-prongs, the momentum of each track was required to be greater than 1 GeV/c. Non-instrumented regions of the detector were avoided by requiring that each track be at least 2 cm from the edge of the shower counter modules and lie in the angular region $|\cos\theta| < 0.55$. Cosmic rays were rejected by requiring that the time of flight of each track be within 3 ns of the expected time. To reject $e^+e^- \to e^+e^-e^+e^-$ and $e^+e^- \to e^+e^-$ events, no more than one track was allowed to deposit a shower energy larger than 3 GeV or greater than one half of its momentum and the total shower energy was required to be less than 14.5 GeV. The backgrounds from $e^+e^- \to e^+e^-\mu^+\mu^-$ and $e^+e^- \to \mu^+\mu^-$ were rejected by requiring that if both tracks were consistent with being minimum ionizing particles, as seen in the shower counters, then the momentum of at least one track had to be greater than 5 GeV/c, and the momentum of each track had to be less than 11 GeV/c.

The additional selection criteria for four- and six-prong events were as follows: The thrust axis of the events was required to be in the angular region $|\cos\theta| < 0.85$. A source of background in the four-prong events is radiative Bhabha scattering with the photon converting in the beam pipe. These events were rejected by requiring that no more than one track deposit a shower energy greater than 90% of its momentum. Low multiplicity hadronic events were reduced by requiring that the invariant mass of the three-prong jets be less than 1.6 GeV/c^2 and, for six-prong events, that the scalar sum of the charged momenta be greater than 12 GeV/c.

These selection criteria yield 1380 two-prong, 1699 four-prong and 164 six-prong events, for a total of 3243 events.

The detection efficiencies for the three different topological final states have been estimated using a Monte Carlo simulation. The simulation produces τ-pair events according to the standard electroweak theory, including the α^3 QED corrections [4]. Each τ is allowed to decay according to the branching ratios in the Particle Data Book [5] [‡1]. The simulation reproduces the data well. For example, the measured scalar sum of the charged momenta for two-, four- and six-prong events is compared with the Monte Carlo simulation (shown as the histograms) in fig. 1. The

‡1 In addition to the measured tau decay modes, we use a phase space model for the 4 pion final states.

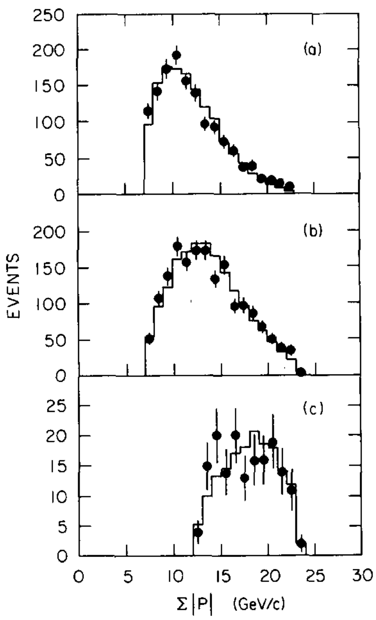

Fig. 1. The distributions in the scalar sum of the charged momenta for (a) two-prong events, (b) four-prong events, and (c) six-prong events. The histograms show the results of the Monte Carlo simulations.

overall detection efficiencies, including geometrical and kinematical cuts are summarized in table 1.

The background contributions have also been estimated by Monte Carlo techniques. Bhabha scattering has both a large cross section and is strongly forward peaked and so is potentially a dangerous background in the two-prong topology. The cuts reduce this contribution to less than 0.1%. The largest background comes from low multiplicity, multi-hadron final states; a comparable background comes from the two-photon process $e^+e^- \to e^+e^-\mu^+\mu^-$. The remaining backgrounds from the reactions $e^+e^- \to e^+e^-\tau^+\tau^-$ and $e^+e^- \to \mu^+\mu^-$ are small. Beam–gas and cosmic ray backgrounds are negligible. The total background is 6.7%, distributed as shown in table 1.

Table 1
Data and background summary.

	Event topology		
	two-prong	four-prong	six-prong
number of events	1380	1699	164
detection efficiency (%)	11	50	41
final state	background fraction (%)		
e^+e^-	< 0.1	–	–
$\mu^+\mu^-$	0.2	–	–
$e^+e^-\mu^+\mu^-$	5.4	–	–
$e^+e^-\tau^+\tau^-$	0.3	0.9	0.0
$q\bar{q}$	–	4.2	30.8

The 2518 events in the central angular region, $|\cos\theta| < 0.55$, were used to measure the absolute cross section. The total integrated luminosity has been measured from the Bhabha events in the same angular region [6]. Our measured cross section divided by the α^3 QED prediction is $R_{\tau\tau} = 1.10 \pm 0.03 \pm 0.04$. The systematic error of 0.04 comes from a 3% uncertainty in the luminosity measurement and an overall 2% error in the calculated detection efficiency, resulting from the uncertainties in the τ decay branching ratios [‡2].

The differential cross section corrected for acceptance, background contamination and the α^3 QED radiative effects is shown in fig. 2. A forward–backward

‡2 The errors in the branching ratios used in the calculation of the detection efficiency error are taken from ref. [5].

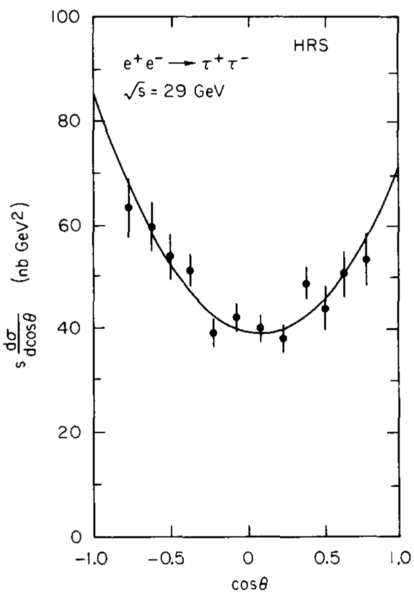

Fig. 2. The differential cross section for the reaction $e^+e^- \to \tau^+\tau^-$ at $\sqrt{s} = 29$ GeV. The curve is the best fit to the data including electroweak interference.

Table 2
Charge asymmetries and axial-vector coupling constants measured by PEP and PETRA experiments.

Detector	Ref.	$A_{\tau\tau}$ (%)	$g_a^\tau g_a^e$	$\sqrt{s}$ (GeV)
HRS		−6.1 ± 2.3 ± 0.5	0.28 ± 0.11 ± 0.03	29
Mark II	[10]	−4.2 ± 2.0	0.19 ± 0.09 ± 0.02	29
Cello	[11]	−10.3 ± 5.2	0.28 ± 0.14	32.0–36.8
Mark J	[12]		0.21 ± 0.18	12.0–36.7
Pluto	[13]		0.19 ± 0.24 ± 0.02	27.5–31.6
Tasso	[14]	−4.9 ± 5.3 ± 1.3	0.13 ± 0.18	13.9–43.1

asymmetry is evident. The full solid angle charge asymmetry, $A_{\tau\tau}$, is defined as $A_{\tau\tau} = (N_f - N_b)/(N_f + N_b)$, where N_f (N_b) is the number of events with the τ^+ in the forward (backward) hemisphere with respect to the e^+ beam direction. In the uncorrected data sample, there are 1576 events in the forward hemisphere and 1667 events in the backward hemisphere. The result of fitting the angular distribution is $A_{\tau\tau} = -(6.1 \pm 2.3 \pm 0.5)\%$, including the α^3 QED contribution of +0.7%. The χ^2 of the fit is 11.6 for 10 degrees of freedom. The systematic error of 0.5% includes the error in the background subtraction as well as an estimate of possible detector bias [6]. The weak radiative corrections [4,7,8] are not included in the above number; they could change the predicted asymmetry by about 0.3%.

The standard model [1] predicts the differential cross section to be:

$$d\sigma/d\cos\theta = (\pi\alpha^2/2s)[R_{\tau\tau}(1+\cos^2\theta) + A\cos\theta],$$

where

$$R_{\tau\tau} = 1 + 2g_v^\tau g_v^e \operatorname{Re}\chi, \quad A = 4g_a^\tau g_a^e \operatorname{Re}\chi,$$

$$\chi = (4\sin^2\theta_W\cos^2\theta_W)^{-1}[s/(s - M_Z^2 + iM_Z\Gamma_Z)]\cdot$$

with the interference terms included. The charge asymmetry is then $A_{\tau\tau} = 3A/8R_{\tau\tau}$. The standard model values for the vector and axial-vector coupling constants are $g_v^\tau g_v^e = 0.25\,(1 - 4\sin^2\theta_W)^2 = 0.0036$ and $g_a^\tau g_a^e = 0.25$, for $\sin^2\theta_W = 0.22$, where θ_W is the Weinberg angle. Assuming a Z mass of 93 ± 2 GeV [9], the predicted values of $A_{\tau\tau}$ and $R_{\tau\tau}$ at $\sqrt{s} = 29$ GeV are $A_{\tau\tau} = -5.9\%$ and $R_{\tau\tau} = 1.00$. Our measurements are therefore consistent with these predictions.

With the above values of $\sin^2\theta_W$ and M_Z, and our measurement of $A_{\tau\tau}$ and $R_{\tau\tau}$, the axial-vector coupling constant is computed to be $g_a^\tau g_a^e = 0.28 \pm 0.11 \pm 0.03$, in good agreement with the standard model prediction and the published results of other experiments at PEP and PETRA, as shown in table 2.

We have reported elsewhere [6] values of $R_{\mu\mu} = 0.990 \pm 0.017 \pm 0.030$ and $A_{\mu\mu} = -(4.9 \pm 1.5 \pm 0.5)\%$. Our μ and τ results are consistent with μ–τ universality. Assuming e–μ–τ universality and combining these results, we measure a lepton axial-vector coupling constant of $g_a^2 = 0.23 \pm 0.06 \pm 0.03$.

Since the effect of the weak interaction on $R_{\tau\tau}$ is expected to be small, we can use our measurement of $R_{\tau\tau}$ to test QED. With the QED cutoff parameters defined by

$$\sigma_{\text{measured}} = \sigma_{\text{QED}}[1 \mp s/(s - \Lambda_\pm^2)]^2,$$

our data give $\Lambda_+ > 92$ GeV and $\Lambda_- > 246$ GeV at 95% CL. These limits are comparable with the results from other PEP and PETRA experiments [11,13,14].

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References

[1] S.L. Glashow, A. Salam and S. Weinberg, Rev. Mod. Phys. 52 (1980) 515.
[2] B. Naroska, Proc. XI Intern. Symp. on Lepton and photon interactions at high energy, ed. N.B. Mistry (Cornell University, Ithaca, NY, 1983) p. 96.
[3] D. Bender et al., Phys. Rev. D30 (1984) 515.
[4] F.A. Berends and R. Kleiss, Nucl. Phys. B177 (1981) 237;
F.A. Berends, R. Kleiss and S. Jadach, Nucl. Phys. B202 (1982) 63.
[5] Particle Data Group, Rev. Mod. Phys. 56 (1984) No. 2, Part II.
[6] M. Derrick et al., New results on the reaction $e^+e^- \to \mu^+\mu^-$ at $\sqrt{s} = 29$ GeV, Argonne National Laboratory ANL-HEP-PR-84-71 (1984), to be published.

[7] R.W. Brown, K. Decker and E.A. Paschos, Phys. Rev. Lett. 52 (1984) 1192.
[8] M. Böhm and W. Hollik, Nucl. Phys. B204 (1982) 45; Z. Phys. 23 (1984) 31.
[9] UA1 Collab., G. Arnison et al., Phys. Lett. 126B (1983) 398;
UA2 Collab., P. Bagnaia, Phys. Lett. 129B (1983) 130.
[10] MARK II Collab., M.E. Levi, Phys. Rev. Lett. 51 (1983) 1941.
[11] CELLO Collab., H.-J. Behrend et al., Phys. Lett. 114B (1982) 282.
[12] MARK J Collab., D.P. Barder et al., Phys. Rev. Lett. 46 (1981) 1663.
[13] PLUTO Collab., Ch. Berger et al., Z. Phys. 7 (1981) 289; Phys. Lett. 99B (1981) 489.
[14] TASSO Collab., M. Aethoff et al., DESY 84-091, submitted to Z. Phys.