DETERMINATION OF THE τ LIFETIME IN HIGH ENERGY e^+e^- ANNIHILATIONS

TASSO Collaboration

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We have determined the τ lifetime in e^+e^- annihilations at an average centre of mass energy of 42.5 GeV, using a pressurized drift chamber close to the interaction point. We find the lifetime to be $(3.18^{+0.59}_{-0.75} \pm 0.56) \times 10^{-13}$ s. The charged weak τ coupling constant relative to that of the μ is found to be $G_\tau / G_\mu = 0.94^{+0.12}_{-0.09} \pm 0.09$, in good agreement with lepton universality.

The properties of the point-like leptons e, μ and τ are of fundamental importance for a theoretical understanding of the constituents of matter. Thus far all experimental evidence suggests that the e, μ and τ have identical properties except for effects due to their different masses. However, the coupling of the τ to the charged intermediate vector boson is still much less well determined than those of the e and μ. The only presently accessible experimental way to determine this coupling is to measure the τ lifetime. Earlier measurements [1] were limited by poor resolution near the event vertex. Recently, the MARK II group at SLAC has determined the τ lifetime with improved vertex resolution using a high precision drift chamber [2]. In this paper we present a τ lifetime measurement obtained in a similar manner using a high precision drift chamber (vertex detector) installed close to the interaction region in the TASSO detector at the PETRA e^+e^- storage ring.

The upgraded TASSO central detector is shown in fig. 1. In September 1982 the original aluminium beam pipe was removed and the vertex detector installed. The vertex detector is mounted rigidly on a beam pipe of 6.5 cm radius which serves as the inner wall of the chamber. The pipe is made from 1.8 mm thick beryllium (0.5% radiation length), coated on the inner surface with a 15 μm thick layer of copper designed to reduce the penetration of synchrotron radiation. The vertex detector has an active length of 57.2 cm and is composed of two groups of four radial layers of sense wires parallel to the beam axis. Each of the inner four layers has 72 wires, while each of the outer four has 108 wires. The inner most layer has a radius of 8.1 cm, the outermost a radius of 14.9 cm. The average radial position for the inner group of wires is 9.1 cm and for the outer group 13.9 cm. The maximum drift distance varies from layer to layer between a minimum of 3.5 mm and a maximum of 4.5 mm. The chamber has an outer wall of 1.5 mm thick aluminium and is designed to enable pressurisation up to 4 bar. The total thickness of the beam pipe, detector and gas is 1.1% of a radiation length; the outer wall adds an extra 1.7% of a radiation length.

The vertex detector is filled with a mixture of 95% argon and 5% carbon dioxide at a pressure of 3 bar. The hit efficiency of the detector is $\geqslant$98%.The spatial resolution in the plane perpendicular to the beam was measured using beam associated two-track events. The resolution averaged over the complete cell varies between 90 and 100 μm. A similar resolution is obtained from $\tau \to 1$ charged track decays where the single track is well separated. For $\tau \to 3$ charged tracks decays, however, where the three tracks are often extremely close because of the large boost involved, the spatial resolution deteriorates to ~130 μm. The information from the vertex detector is combined with that of the large drift chamber [3] to find the overall track parameters. The relative alignment between the vertex detector and the drift chamber is known to an accuracy of $\sim 10^{-4}$ rad, azimuthally and 100 μm in x (horizontal)

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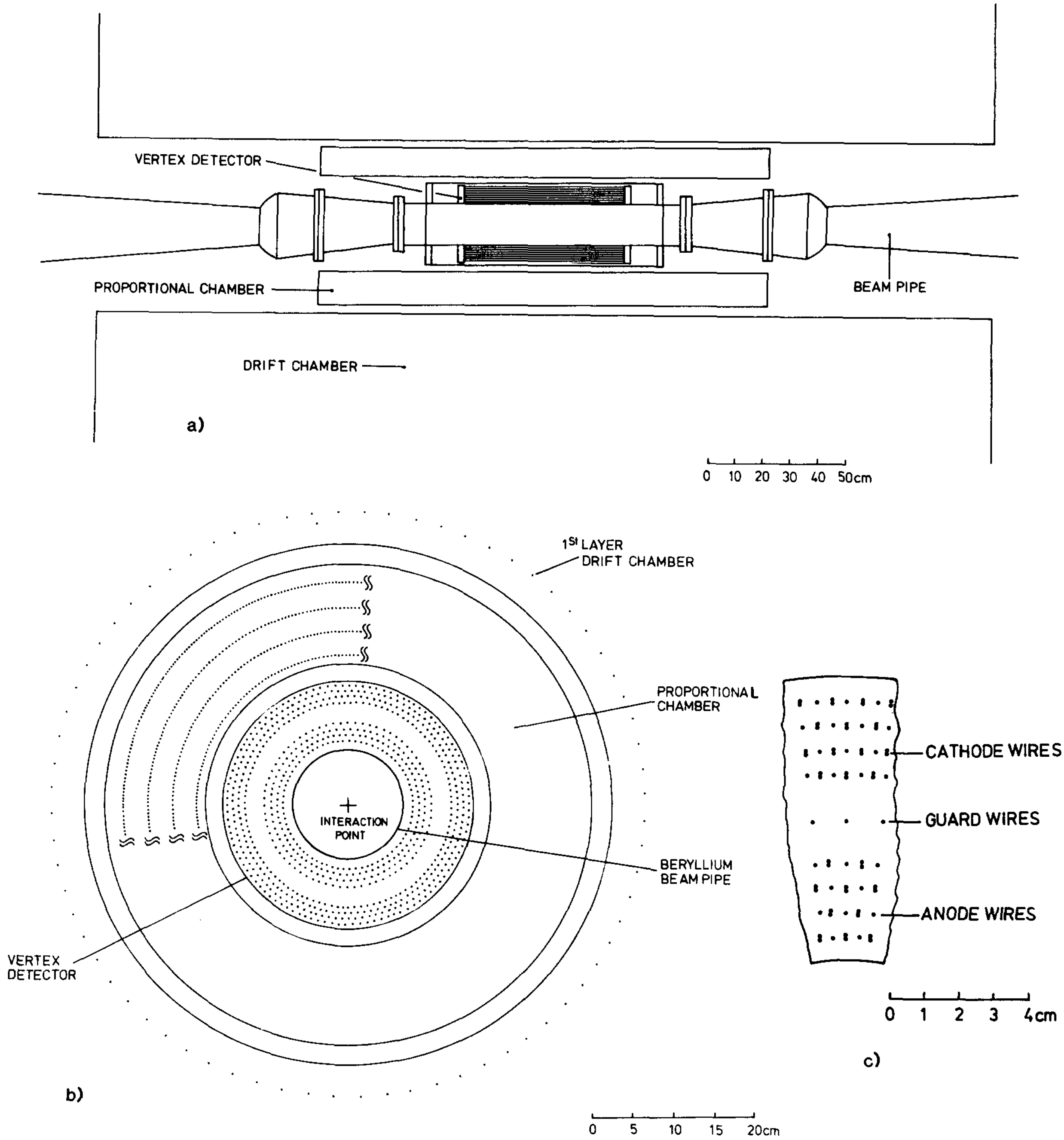

Fig. 1. (a) The inner part of the TASSO central detector viewed perpendicular to the beam direction. (b) The inner part of the TASSO central detector viewed along the beam direction. (c) Schematic view of the cell configuration in the vertex detector.

and y (vertical), the coordinates perpendicular to the beam. The combination of vertex detector and drift chamber leads to a momentum resolution of $\sigma_p/p \sim 0.0095\, p$ (p in GeV/c) for high momentum $e^+e^- \to \mu^+\mu^-$ events. The TASSO detector is described in more detail in ref. [3]; more information on the vertex detector itself may be found in ref. [4].

The data presented here were collected in 1983 during an energy scan in 30 MeV steps in centre of mass energy from 39.8 GeV to 45.2 GeV. The average CM energy was 42.48 GeV, and the total luminosity collected was 10.2 pb^{-1}.

The selection of candidates for the reaction $e^+e^- \to \tau^+\tau^-$ in the TASSO detector has been described previously [5] and therefore will be only briefly discussed here. At the centre of mass energies of this experiment τ-pair production has a distinctive signature with very small contaminations from other processes, We accepted events with two well collimated groups of particles. One group was required to have three charged tracks which when interpreted as pions, gave an effective mass < 2.0 GeV. The other group was required to contain either one track (referred to as "1 + 3" topology) or three tracks with an identical mass cut of 2.0 GeV (referred to as "3 + 3" topology).

In order to minimize the background from $e^+e^- \to e^+e^-\gamma\gamma$ processes, the sum of the total momenta of the charged tracks was required to be ≥ 5 GeV/c. To estimate the remaining background we used the program of Berends et al. [6] to generate the reactions $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-\tau^+\tau^-$ and $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-$ + hadrons. The tracks generated were passed through our detector simulation program and the same pattern recognition program as used for the data. The background from $e^+e^- \to e^+e^-$ hadrons was found to be negligible, while that from $e^+e^- \to e^+e^-\tau^+\tau^-$ was estimated to be ~ 0.7 events for the "1 + 3" topology and ~ 0.3 events for the "3 + 3" topology.

Bhabha scattering events where one of the electrons radiates a photon which converts in the detector material can give a topology similar to $e^+e^- \to \tau^+\tau^-$ production. To reduce the Bhabha scattering background the minimum effective mass of pairs of oppositely charged tracks (assumed for this purpose to be electrons) was required to be ≥ 0.15 GeV/c. The remaining background was reduced to a negligible level by scanning the selected events.

The contribution from the process $e^+e^- \to$ hadrons was found using the Lund [7] and Hoyer [8] generators for $e^+e^- \to q\bar{q}$, $q\bar{q}g$ and normalizing their predictions to the low multiplicity side of the charged particle multiplicity distribution obtained from the data. While the two programs gave some differences in the predicted number of events, in no case was a significant background from this process found. A background of 0.2 events for the "1 + 3" sample and 0.4 events for the "3 + 3" sample was estimated.

The events selected on the basis of the above cuts were scanned and those containing a badly reconstructed track or more than one track with less than three associated vertex detector hits were excluded. A total of 37 "1 + 3" topology and 11 "3 + 3" topology events remained. The background from the other processes detailed above was 0.9 events for the "1 + 3" sample and 0.7 events for the "3 + 3" sample.

The τ lifetime was determined in two ways:

(a) by measuring the distance between the production point of the τ and its decay vertex. In this case all track vertices from the "1 + 3" and "3 + 3" topologies were used.

(b) By measuring the separation of the two decay vertices in a "3 + 3" topology $e^+e^- \to \tau^+\tau^-$ event, which is the sum of the flight paths of the two τ particles.

The rationale for using two different methods is that the systematic errors for (a) and (b) are different: Method (a) requires an estimate of the production point of the τ, which lies within the luminous region formed by the overlap of the electron and positron beams. The position of this region was determined for individual fillings of PETRA. Method (b) eliminates the uncertainty inherent in this procedure; however, the accuracy obtained is limited by the smaller number of "3 + 3" topology events. In the following we first describe the fitting procedure used to determine the position of the τ decay vertex, then discuss the steps employed in method (a). We use method (b) as a consistency check on the result of method (a).

For each track we used the hit information from all three chambers, vertex detector, proportional chamber and drift chamber. Before constraining the tracks to a common vertex, the fitting program was allowed to delete up to three points from each track if the χ^2 for that track fit was too high.

The vertex fit was carried out by contraining the three tracks to come from a common point. The χ^2

formed by comparing the hits associated with each track with the predicted track position was then minimized by varying the parameters of the track and the position of the common vertex. Multiple scattering was taken into account in both track and vertex fit. It was assumed for the purpose of computation to occur at a radius of 16 cm, between the vertex detector and the drift chamber, with the average multiple scattering angle increased by 30%. This parametrization was checked by Monte Carlo simulation and comparison with data and found to give a good description of the error matrix for the vertex fit. The uncertainty in the error matrix elements given by this model was estimated to be ~20%. The program first attempted a fit in three dimensions. If the increase in overall χ^2 compared to that without a vertex constraint was significantly higher than would be statistically expected, a fit in two dimensions was tried. If this too failed the χ^2 criterion, then a fit in the vertex detector alone was attempted. If all three fits failed, the vertex was rejected. From our sample of 59 three-track vertices, 4 failed the vertex fit. The above procedure gave the vertex position and the full error matrix for each successful fit.

The beams have a finite size and the position of the interaction region with respect to the tracking chambers can also vary due to changes in the PETRA optics or mechanical variations in the positions of the tracking chambers. We monitored these changes on a run-to-run basis by using tracks from beam associated events. At least 50 clean tracks with ⩾4 vertex detector hits had to be accumulated for each determination of the beam position. The uncertainty in the beam position was typically 150 μm in x and y. No attempt was made to determine the z position of the interaction region because its size is several centimeters. The RMS beam size in x and y has been calculated from the machine lattice and optics parameters to be ~500 μm, 10 μm respectively [9]. Because the uncertainty of the beam position in y is larger than its size, the appropriate quantity for use in our fit in this case is the uncertainty in the position. In our determination we used $\sigma_x = 530$ μm, $\sigma_y = 150$ μm for the dimensions of the luminous region.

Having obtained the centre of the interaction region and the coordinates of the secondary τ vertex it can be shown that the best estimate of the decay length projected in the xy-plane is given by

$$l_{xy} = \frac{x_v \sigma_{yy} t_x + y_v \sigma_{xx} t_y - \sigma_{xy}(x_v t_y + y_v t_x)}{t_x^2 \sigma_{yy} - 2\sigma_{xy} t_y t_x + \sigma_{xx} t_y^2},$$

where σ_{ij} are the elements of the error matrix formed by adding the error matrices for the primary and secondary vertices, t_x, t_y are the direction cosines of the τ found by adding the momenta of three tracks from the secondary vertex (which approximates the direction of flight of the τ), x_v, y_v are the coordinates of the secondary vertex relative to the beam position. The total decay length l was then obtained in three dimensions by using the z component of the momentum vector of the three tracks from the τ decay. From the above expression for l_{xy} the error, σ_l, on l was calculated for each event. The distribution function for the decay paths was obtained from a convolution of a gaussian resolution function with an exponential decay distribution. We obtained the best value for the lifetime by carrying out a maximum likelihood fit.

The distribution of errors is shown in fig. 2. It peaks at 1100 μm with a mean of 1400 μm. After discarding events with an error greater than 2500 μm, 50 three-track vertices survived. Fig. 3 shows the distribution of τ decay lengths. The mean of this distribution is 1051 ± 270 μm, which is significantly different from zero. The maximum likelihood fit gives 1082^{+205}_{-261} μm as the best estimate for the τ decay length. The distribution function for this result is shown as the solid line in fig. 3, and fits the distribution well.

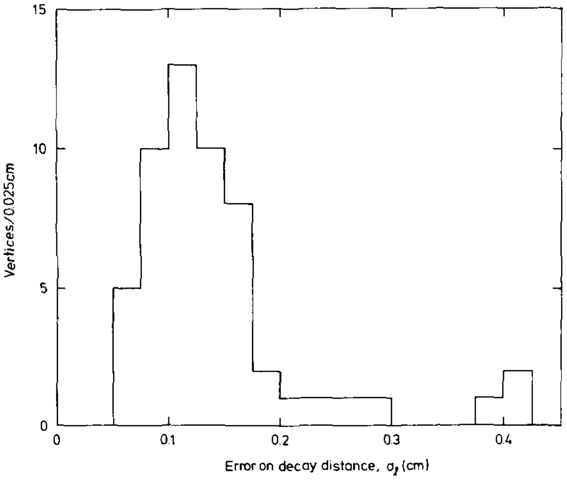

Fig. 2. The distribution of the error on the decay distance, σ_l, for $\tau \to$ three charged tracks.

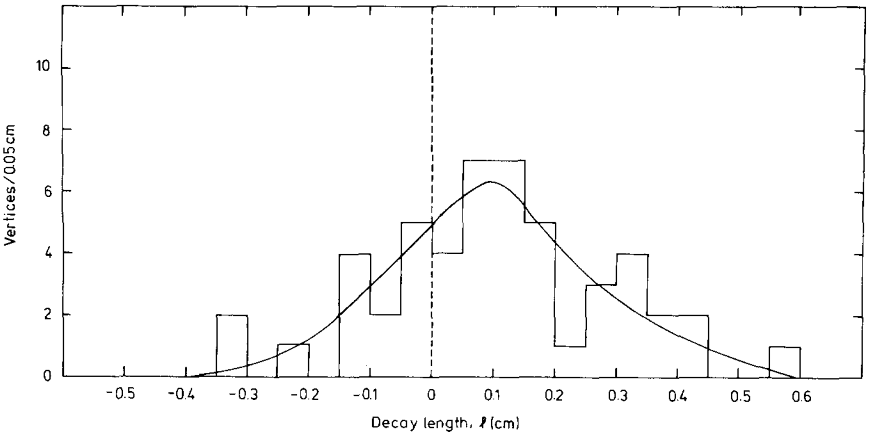

Fig. 3. The distribution of decay distances for $\tau \to$ three charged tracks. The solid curve shows the best fit to this distribution as described in the text.

We investigated several possible sources of systematic errors in the result. To check that the vertex fit and maximum likelihood estimate reconstructed the correct lifetime, we generated $e^+e^- \to \tau^+\tau^-$ Monte Carlo events with a full simulation of the tracking chambers of the TASSO detector and passed them through the standard track reconstruction and $\tau^+\tau^-$ selection programs used for the data. The generated mean decay lengths were 0 μm, 834 μm and 1500 μm; the best estimates for the reconstructed decay lengths after track reconstruction and vertex fitting from ~250 accepted Monte Carlo events for each case were 147 ± 90 μm, 789^{+100}_{-118} μm, 1630^{+163}_{-180} μm, in good agreement with the input values.

We investigated systematic errors due to possible misalignment of the chambers by varying the vertex detector position by $\pm 2\sigma$ from the nominal values; while the resolution worsened slightly, the mean decay length changed by $\lesssim$10%. Similarly, the position of the beam was displayed randomly from run to run by ~20 μm. Wile this again increased the error on the determination, it produced a negligible shift in the mean decay length. We checked the effect of a possible tilt of the chamber with respect to the z axis by using only τ's within a polar angle region of 60°–130°; the reconstructed decay length was 1067^{+262}_{-353} μm, in good agreement with that found for all the data.

We checked that the data showed no bias comparable to our observed τ decay lengths by forming combinations of three tracks, each with $p > 0.5$ GeV/c, from events from the process $e^+e^- \to$ hadrons, satisfying the τ selection criteria. This combination of tracks was reconstructed in the same way as the $\tau^+\tau^-$ candidates. The decay length distribution fitted well to a gaussian whose width was within 20% of our calculated value and whose mean was 54 ± 120 μm, compatible with no bias.

The assumption that the errors were gaussian and centered around the true value was checked by generating zero lifetime $\tau^+\tau^-$ events and plotting the reconstructed decay length divided by the calculated error. This distribution fitted well to a gaussian; furthermore, the width was equal to unity to within 10%. This was also checked using the $\tau^+\tau^-$ data by allowing a scaling factor for σ_l, as well as the exponential decay length, to vary in the maximum likelihood fit. The value of the scaling factor obtained, 1.11 ± 0.15, confirms that the data required no statistically significant correction to our calculated errors. Similarly, by allowing an offset to vary in the fit, we found no evidence for any bias.

We also checked the internal consistency of our sample. In particular we compared the means of the decay distances using only the "1 + 3" or the "3 + 3" topology sample, and the three-dimensional or the two-dimensional vertex fits. In all cases no statistically significant deviation of the reconstructed decay length was observed.

We estimate the systematic error for method (a) from contributions to the uncertainty of the mean decay length. We obtain ±100 μm from the uncertainty in our calculation of the error, σ_l; ±120 μm from a possible offset in the resolution function; ±100 μm from uncertainties in the relative alignment of the chambers and the position of the interaction region, giving an overall systematic error of 190 μm.

As a final check on our result we used method (b) to obtain the τ decay distance from the "3 + 3" topology sample. After identical vertex reconstruction and cuts, 7 "3 + 3" events with both three-track vertices well reconstructed survived. The mean separation of the two three-track vertices, which is independent of the production point, was found to be 3200^{+1100}_{-1600} μm, and hence gave a mean decay distance of 1600^{+550}_{-800} μm, in good agreement with that deduced from method (a). Since, as was remarked earlier, method (b) has different systematic errors from method (a), this serves as a further consistency check on our result.

In conclusion, we obtain a mean τ decay length of $1082^{+205}_{-261} \pm 190$ μm. The τ lifetime was determined by calculating the decay time for each τ and fitting this distribution. Correcting for an average 7% loss in the mean τ energy due to radiation of photons in the initial state, we obtain a τ lifetime of

$$\tau(\tau) = (3.18^{+0.59}_{-0.75} \pm 0.56) \times 10^{-13}\ \mathrm{s}.$$

Our result is in good agreement with the value given in ref. [2],

$$\tau(\tau) = (3.20 \pm 0.41 \pm 0.35) \times 10^{-13}\ \mathrm{s}.$$

If lepton universality holds, the τ lifetime is predicted to be

$$\tau(\tau) = \tau(\mu)\,(m_\tau/m_\mu)^5\ \mathrm{BR}(\tau \to e\nu\bar{\nu})$$

$$= (2.8 \pm 0.2) \times 10^{-13}\ \mathrm{s},$$

where we have assumed a value of 0.175 [11] for the decay branching ratio $\mathrm{BR}(\tau \to e\nu\bar{\nu})$. Our result is in good agreement with this prediction and leads to a value of the charged coupling constant G_τ of

$$G_\tau/G_\mu = 0.94^{+0.12}_{-0.09} \pm 0.09,$$

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