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by

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A Measurement of the τ Lifetime

The TASSO Collaboration

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Abstract

We have reconstructed 695 three-track τ decay vertices using a high resolution drift chamber close to the interaction point. From the distribution of decay lengths we measure the lifetime to be $(3.06 \pm 0.20 \pm 0.14) \times 10^{-13}$ s. Using this result we find that the ratio of charged weak coupling constant for the τ to that of the μ, $G_\tau/G_\mu = 0.967 \pm 0.040$ consistent with the concept of lepton universality.

I Introduction

All present experimental evidence supports the idea that the charged leptons e,μ and τ have identical properties, except for effects due to their different masses. This property of lepton universality, together with the fact that the mass of the tau neutrino has been shown to be negligible [1], allow us to relate the τ lifetime (τ_τ) to that of the μ (τ_μ) as follows:

$$\tau_\tau = \tau_\mu (m_\mu/m_\tau)^5 BR(\tau \longrightarrow e\nu\bar{\nu})$$

where m_μ and m_τ are the μ and τ masses respectively. Radiative corrections are expected to be small [2] and have been neglected. Recent precision measurements have determined the branching ratio $BR(\tau \longrightarrow e\nu\bar{\nu})$ to be $17.9 \pm 0.4\%$ [3], and allow one to predict $\tau_\tau = (2.86 \pm 0.07) \times 10^{-13}$ s. It is therefore of interest to measure τ_τ with comparable precision, particularly because of the possible discrepancy between the measured topological branching ratio of the τ to one charged particle plus neutrals, and the sum of the individual decay modes [3].

We have previously presented a measurement of τ_τ [4], based on an integrated luminosity of 10.2 pb^{-1}. The analysis presented here is essentially similar, but includes all the data collected by TASSO after the installation of a vertex detector (VXD). The total luminosity collected was 159.2 pb^{-1}, at an average centre of mass (cm) energy of 36.3 GeV. Most of the data (110.5 pb^{-1}) were collected during 1986 at a cm energy of 35.0 GeV. The additional data and the stable data taking conditions have allowed us to improve significantly our understanding of the systematic errors present in our analysis.

A general description of the TASSO detector can be found elsewhere [5]. Two components, the large cylindrical drift chamber (DC) [6] and the VXD [7], were used extensively in this analysis, and are therefore briefly described here. The coordinate system and track parameters are shown in figure 1. The DC consisted of 15 layers of drift cells at radii between 36 cm and 122 cm. Six layers consisted of small angle stereo wires, which provided all the polar angle information used in tracking. Within the DC, and also within a cylindrical proportional chamber and attached to the beampipe was the VXD. This consisted of eight drift cell layers (measuring only $r - \phi$ coordinates) at radii between 8.1 cm and 14.9 cm. The VXD was operated using a gas mixture of 95% argon and 5% carbon dioxide, at a pressure of 3 bar.

Because the VXD was not physically attached to the DC, it was necessary to measure precisely their relative alignment, defined in terms of 2 translational shifts and 3 Euler angles. To do this, we used a sample of two-track e^+e^- annihilation events. Tracks found in the DC were extrapolated into the VXD and associated with hits [8]. By looking at the mean displacement of the VXD hits with respect to the tracks found in the DC as a function of the track orientation [9], we were able to determine the relative position in x and y to a precision of 25 μm, and the rotations to a precision of 0.02 mrad. The alignment was found to be stable for long periods.

II Event selection

We selected $e^+e^- \longrightarrow \tau^+\tau^-$ events, where one τ decays into three charged particles plus undetected neutrals and the other into one or three charged particles plus undetected neutrals : (1-3) and (3-3) topologies. Using track information from the DC we were able to isolate a sample of events, based on the distinct topology and kinematics of τ decays at PETRA energies. The selection criteria were similar to those used in our previous work [4,11]. The cuts are listed in detail in the appendix.

Using these cuts, we selected from our data sample a total of 1374 events of the (1-3) topology and 119 events of the (3-3) topology. The tracks found in the DC were extrapolated into the VXD and associated with hits [8], with the requirement that at least four VXD hits be found for each track. These events were scanned in order to remove residual contamination from (i) two-prong scattering events where a radiated photon has converted to an e^+e^- pair and (ii) obvious non-τ events. The scan rejected a total of 27 events of the (1-3) topology and 2 events of the (3-3) topology. This left 735 (1-3) events and 49 (3-3) events, a total of 829 three-track τ decay vertices suitable for lifetime measurement.

Using standard Monte Carlo methods of detector simulation [12] we investigated several sources of background processes. We estimated [13,14] the background from multihadron events to be $1.1 \pm 0.5\%$ in the (1-3) topology and $8.0 \pm 3.3\%$ for the (3-3) topology. Likewise [15], the contribution from two photon τ pair production was found to be $3.2 \pm 0.5\%$ and $3.4 \pm 0.9\%$ respectively. It was found that the contamination from radiative Bhabha scattering and μ-pair production could be readily identified.

III Lifetime measurement

To determine the τ decay length we measured the position of both the production and decay vertices. The production vertex lies within the overlap region of the electron and positron beams (the beam spot). The beam spot was found to be rather sensitive to changes in the operation of PETRA, so we measured its position on a fill-by-fill basis, averaging sequential fills only when insufficient data existed from a single filling. Since the size of the interaction region in z extended over several centimetres, and owing to our relatively poor tracking information in z, we only determined the x and y coordinates of the beam spot.

To find the best estimate for the beam spot we used tracking information from the VXD combined with the momentum measurements from the DC [8], and selected beam associated tracks, requiring at least 50 tracks per event sample for an accurate determination. A χ^2 for each track was defined as follows:

$$\chi_i^2 = \frac{d_i^2}{\sigma_d^2} + \frac{(x_i - x_b)^2}{\sigma_x^2} + \frac{(y_i - y_b)^2}{\sigma_y^2}.$$

Where d_i is the impact parameter made with the hypothesised interaction point (x_i, y_i) for the event and (x_b, y_b) is the most likely centre of the beam spot. The errors σ_x and σ_y correspond to the rms size of the interaction region which were estimated to be 500 μm and 60 μm respectively. The beamspots obtained were found not to be sensitive to changes in these sizes. σ_d is the sum in quadrature of a term representing the intrinsic detector impact parameter resolution (σ_{track}) and a multiple scattering term, which is inversely proportional to the momentum of the track. By minimising each χ_i^2, with respect to (x_i, y_i), the χ_i^2 can be expressed in terms of the track parameters (see figure 1), allowing a global χ^2 to be formed:

$$\chi^2 = \sum \chi_i^2(\phi_{0_i}, d_{0_i}, x_b, y_b).$$

This expression was minimised to extract (x_b, y_b), together with its error. The beam spot positions in x and y for the 1986 period are shown in figure 2. It can be seen that the beam spot was considerably more stable in y than in x, as would be expected from the operation of the storage ring. Periods of instability within a fill were systematically excluded from this lifetime analysis, by requiring the χ^2 per degree of freedom to be less than 2.0. This resulted in the rejection of 8 τ pair events.

Having obtained the beam positions, we used our 2-track sample to make an accurate measurement of the rms sizes of the interaction region, σ_x and σ_y, which included possible effects due to beam movement. By measuring the width of the distribution of impact parameters (with respect to (x_b, y_b)) as a function of ϕ_0, we found that the size of the interaction region varied between 300 μm and 520 μm in x, and 60 μm and 120 μm in y, depending on the beam energy, and the stability of its position. A typical result is illustrated in figure 3. The final errors on the production point were taken as the measured size added in quadrature with the errors on the position determination.

To find the decay vertex we refitted the tracks from each τ decay, using $r-\phi$ information from both the DC and VXD and adding the constraint that they should share a common production point [10]. Included in this fit were χ^2 terms which allowed for multiple scattering. The scattering material was taken to be concentrated at two fixed radii, 7.0 cm and 16.0 cm. The rms scattering angles were calculated assuming that a particle travelling in the $r-\phi$ plane would pass through material corresponding to 0.71% and 7.73% of a radiation length, repectively, at these radii. This description modelled well the actual configuration of the TASSO detector, and Monte Carlo studies [12,16] showed that τ decay vertices were correctly reconstructed, even for rather low track momenta.

In refitting the tracks, we took particular care to understand the spatial resolutions of the two drift chambers. These are needed to calculate the errors associated with the reconstructed vertices. To measure the resolutions we used refitted tracks [10], without the vertex constraint. We compared the rms widths of the residual distributions for the τ data with Monte Carlo, adjusting the Monte Carlo resolution parameters until they matched. The effects of noise background were included in the Monte Carlo simulations, by superimposing random trigger data events. The rms resolutions obtained for each of the eight VXD layers varied between 108 μm and 154 μm. The variation of the resolution between the different layers can be understood in terms of different high voltage settings, discriminators, and the termination of the sense wires [7,9]. We also studied the variation of the resolution with drift distance. It was found to be reasonably constant, except near the half-cell edges. These variations in

resolution were used in the subsequent refits. The measured rms resolution of the DC was 256 μm. The values are significantly larger than the resolutions previously obtained using two-track events [6,7]. Most of the degradation occurs because of the close proximity of the three tracks, which makes track finding more difficult and the false assignment of hits more likely. By varying the track selection criteria, and by studying the non-Gaussian effects, which were present particularly near the half-cell edges, we estimate the systematic uncertainty in the resolutions to be 10%.

Before constraining the tracks to vertices, we checked the confidence level of each track fit. If this was less than 1%, we attempted to improve it by removing hits from the track and refitting [10]. If after removing two hits the confidence level was still less than 1%, or if there were fewer than four VXD hits remaining, we rejected the event. Monte Carlo simulations showed this technique to be successful in removing hits which had been falsely assigned to the track without significantly biasing the confidence level. The accepted tracks were constrained to vertices, and after rejecting those events in which the confidence level associated with the increase in χ^2 needed to constrain the tracks was less than 1%, 695 vertices remained. A visual scan of the rejected events showed that many contained misassigned hits or low momentum tracks. The rejected events also included 8 vertices consistent with the decay $\tau \longrightarrow K^0\pi\nu$. Monte Carlo studies indicated that such events would be effectively removed by these cuts.

The best estimate for the decay length (l), is given by:

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

Here x_v and y_v are the coordinates of the vertex, relative to the beam spot position and the σ_{ij} are the components of the error matrix, formed by adding the error matrices for the beam spot and the decay vertex. The t_i are the three-dimensional direction cosines of the τ, which were estimated by adding the momenta of the three tracks from the secondary vertex. Monte Carlo studies showed that this approximation did not introduce significant errors. Each decay length (l_i) was transformed into a decay time(τ_i) in the rest frame of the τ using:

$$c\tau_i = \frac{l_i}{\beta\gamma}; \quad \gamma = \frac{rE_{beam}}{m_\tau}.$$

Where β is the velocity of the τ, and the factor r has been introduced to correct for initial state radiation, and the reduced energy of those τ events produced via two photon interactions which remained in our sample. Using Monte Carlo methods [15,16], we found $r = 0.934 \pm 0.004$. The distributions of decay times, and errors, are shown in figure 4. The mean measurement error is $(4.92 \pm 0.07) \times 10^{-13}$ s, and the weighted mean of the decay time distribution is $(2.99 \pm 0.25) \times 10^{-13}$ s.

To extract τ_τ we used a maximum likelihood fit to the measured decay times (τ_i) and their errors (σ_i). The likelihood function was of the form:

$$L(\tau_\tau) = \prod_i \{(1 - P_{back})F(\tau_i, \sigma_i; \tau_\tau) + P_{back}G(\tau_i, \sigma_i)\}.$$

The functions $F(\tau_i, \sigma_i; \tau_\tau)$ represent the exponential lifetime distribution convoluted with Gaussian resolution functions. P_{back} is the residual fraction of hadronic background, and the functions $G(\tau_i, \sigma_i)$ correspond to its apparent decay time distribution. These were assumed to be Gaussian, with a common offset from zero, found from Monte Carlo studies to be $(0.6 \pm 1.0) \times 10^{-13}$ s.

The fit was performed using two parameters, τ_τ and a common error scaling parameter (k). Systematic errors, in particular those associated with the detector resolutions, result in a rescaling of the decay time errors. These systematic uncertainties can be absorbed into the parameter k. If τ_τ had been the only parameter, any unknown scaling factor would change significantly the fitted lifetime. The result of the fit was $\tau_\tau = (3.06 \pm 0.20) \times 10^{-13}$ s and $k = 1.08 \pm 0.04$. The contour intervals corresponding to the errors can be seen in figure 5. The fact that k was consistent with unity confirmed our understanding of the errors associated with the vertex reconstruction. The curve predicted by the maximum likelihood fit has been added to figure 4a. The confidence level associated with the χ^2 of the data points compared with the curve is 0.34.

We investigated several sources of systematic errors. Changes in the detector resolution of $\pm$ 10 % were, as expected, largely absorbed into the error scaling parameter, but resulted in a change of the lifetime by $\pm 0.04 \times 10^{-13}$ s. Changing the relative alignment of the chambers by $\pm 1\sigma$ contributed an error of $\pm 0.06 \times 10^{-13}$ s. Variation of the hadronic background and its apparent lifetime by $\pm 1\sigma$ changed τ_τ by $\pm 0.03 \times 10^{-13}$ s. Uncertainties in r contributed $\pm 0.01 \times 10^{-13}$ s. The analysis was repeated using an independent track finder [17] and the reconstructed decay times were observed to vary somewhat on an event-by-event basis. However, the weighted mean of the differences for the common event sample was $(0.02 \pm 0.10) \times 10^{-13}$ s, clearly consistent with zero. We took the error on the mean difference as a possible systematic error. We also looked for apparent variations of the lifetime with the polar and azimuthal angles of the τ, and for different data taking periods. No significant variations were found.

To study further possible systematic effects we divided our sample according to topology. No significant differences in lifetime were evident. As a further check, we looked at the separation between the two vertices for the (3-3) events. This quantity is important because it has a different distribution and does not use the τ production point. From the 35 events in our sample with two reconstructed vertices, we use half the weighted mean separation to determine $\tau_\tau = (2.5 \pm 0.8) \times 10^{-13}$ s, consistent with the value obtained using the distribution of single decay lengths.

As a further check of our understanding of the vertex reconstruction errors, we selected 'pseudo-tau' events from the TASSO hadronic sample. Triplets of tracks were selected which passed the track selection cuts applied in candidate τ events, and which were separated from each other in the $r - \phi$ plane by less than 35^0. These tracks were required to be isolated from the other tracks in the event by more than 30^0 in the $r - \varphi$ plane. After treating these tracks in exactly the same way as the actual τ decay tracks, we obtained the distribution of decay lengths divided by their errors, shown in figure 6. This is well described by a Gaussian with $\sigma = 1.06 \pm 0.03$ and an offset of 0.14 ± 0.04. Monte Carlo simulations predict an offset of 0.21 ± 0.03 due to the decay of heavy flavoured hadrons. The Gaussian width is consistent with that obtained for the lifetime resolution function, and also with unity, confirming our understanding of the tracking and vertex reconstruction errors.

The analysis procedure was also carefully checked using Monte Carlo techniques [12,16]. We generated a sample equivalent to a luminosity of 1760 pb^{-1}, with a lifetime of 3.00×10^{-13} s. After passing the generated events through the same analysis chain as the data, we measured the mean lifetime to be $(3.05 \pm 0.06) \times 10^{-13}$ s, consistent with the input value. From this and our 'pseudo-tau' studies we take $\pm 0.06 \times 10^{-13}$ s as a conservative estimate of any bias present in our vertex reconstruction technique. In order to be certain that there was a linear relationship between the actual and reconstructed lifetimes, we generated two further Monte Carlo event samples, equivalent to luminosities of 440 pb^{-1}, with lifetimes of 2.00×10^{-13} s and 4.00×10^{-13} s. They were reconstructed to be $2.00^{+0.11}_{-0.10} \times 10^{-13}$ s and $3.90^{+0.14}_{-0.14} \times 10^{-13}$ s respectively. Again there was no evidence of bias.

Adding all the contributions in quadrature, a total systematic error of $\pm 0.14 \times 10^{-13}$ s was obtained.

IV Conclusions

We measure τ lifetime τ_τ to be $(3.06 \pm 0.20 \pm 0.14) \times 10^{-13}$ s. Our measurement is in good agreement with the theoretical prediction, assuming lepton universality and an electronic branching ratio of $BR(\tau \to e\nu\bar{\nu}) = 17.9 \pm 0.4\%$ [3]. By using this ratio, one obtains relative strengths of the Fermi coupling constants for the τ and μ:

$$G_\tau / G_\mu = 0.967 \pm 0.040,$$

where all statistical and systematic errors have been added in quadrature.

Our measurement is also in good agreement with similar results published by other experimental groups [18]. These results, together with our own are summarised in figure 7. The average value, obtained by taking the error on each measurement as the sum in quadrature of its statistical and systematic errors, is $\tau_\tau = (3.06 \pm 0.09) \times 10^{-13}$ s. This is of similar precision to the average electronic branching ratio and corresponds to $G_\tau / G_\mu = 0.967 \pm 0.019$.

Acknowledgements

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Appendix : Selection criteria for τ pair events

For the (1-3) topology the following cuts were applied :

1. There must be exactly four tracks reconstructed in three dimensions, with the sum of all charges $\Sigma Q = 0$, where each track must satisfy (i) $|d_0| < 5.0$cm, (ii) $|z_0| < 5.0$cm, and (iii) $p_{xy} > 0.1$ GeV/c. The event, only considering the accepted tracks, must satisfy the remaining cuts.
2. One track must be separated from the summed momentum vector of the remaining three-track system by more than 100^0. Within the three-track system the maximum angular separation must be $< 35^0$.
3. The sum of the scalar track momenta (p_{tot}) must satisfy: $0.2\ E_{cm} < p_{tot} < 0.9\ E_{cm}$, and each track must have momentum $p < 0.45\ E_{cm}$.
4. The invariant mass of the 3-track system, assuming that these are pions, must be less than 1.9 GeV.
5. The invariant mass of any pair of oppositely charged tracks, assuming that they are electrons, must be greater than 0.12 GeV.

The selection criteria for the (3-3) topology were :

1. There must be exactly six tracks reconstructed in three dimensions, with summed charge $\Sigma Q = 0$, where each track must satisfy (i) $|d_0| < 5.0$cm, (ii) $|z_0| < 5.0$cm and (iii) $p_{xy} > 0.1$ GeV/c. The event, only considering the accepted tracks, must satisfy the remaining cuts.
2. The two three-track systems, each with $|\Sigma Q| = 1$, must have summed momentum vectors separated from each other by $> 100^0$. The maximum angular separation in each system must be $< 40^0$.
3. The summed scalar track momentum (p_{tot}) must satisfy: $0.25\ E_{cm} < p_{tot} < E_{cm}$ and each track must have momentum $p < 0.45\ E_{cm}$.
4. The invariant mass of each 3-track system, assuming that these are pions, must be less than 1.8 GeV.
5. The invariant mass of any pair of oppositely charged tracks, assuming that these are electrons, must be greater than 0.12 GeV.

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Figure Captions

Figure 1: (a) The coordinate system. (b) Definition of track parameters.

Figure 2: The vertex coordinates of the beam spot for the 1986 runs, corresponding to a period of about eight months.

Figure 3: The widths of the two-prong impact parameter distribution at different ϕ_0 angles, for part of the 1986 running period. The errors on the beam sizes are mainly the result of uncertainties in the impact parameter resolution (σ_{track}).

Figure 4: (a) The distribution of decay times, together with the curve which corresponds to the result of the maximum likelihood fit. (b) Distribution of errors on the decay times.

Figure 5: Contours of error scale factor (see text) against τ lifetime. They correspond to increases of the likelihood function by 0.5 (1σ), 2.0 (2σ) and 4.5 (3σ).

Figure 6: The distribution of decay lengths divided by errors for 'pseudo-tau' events. The Gaussian shown was obtained by fitting over the range ±3.

Figure 7: A summary of τ lifetime measurements.

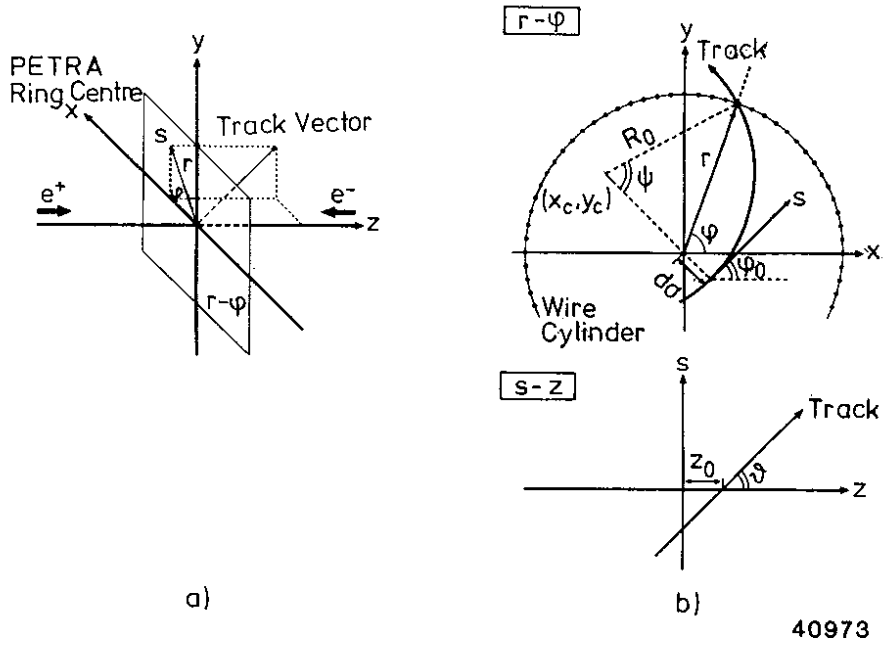

Fig. 1

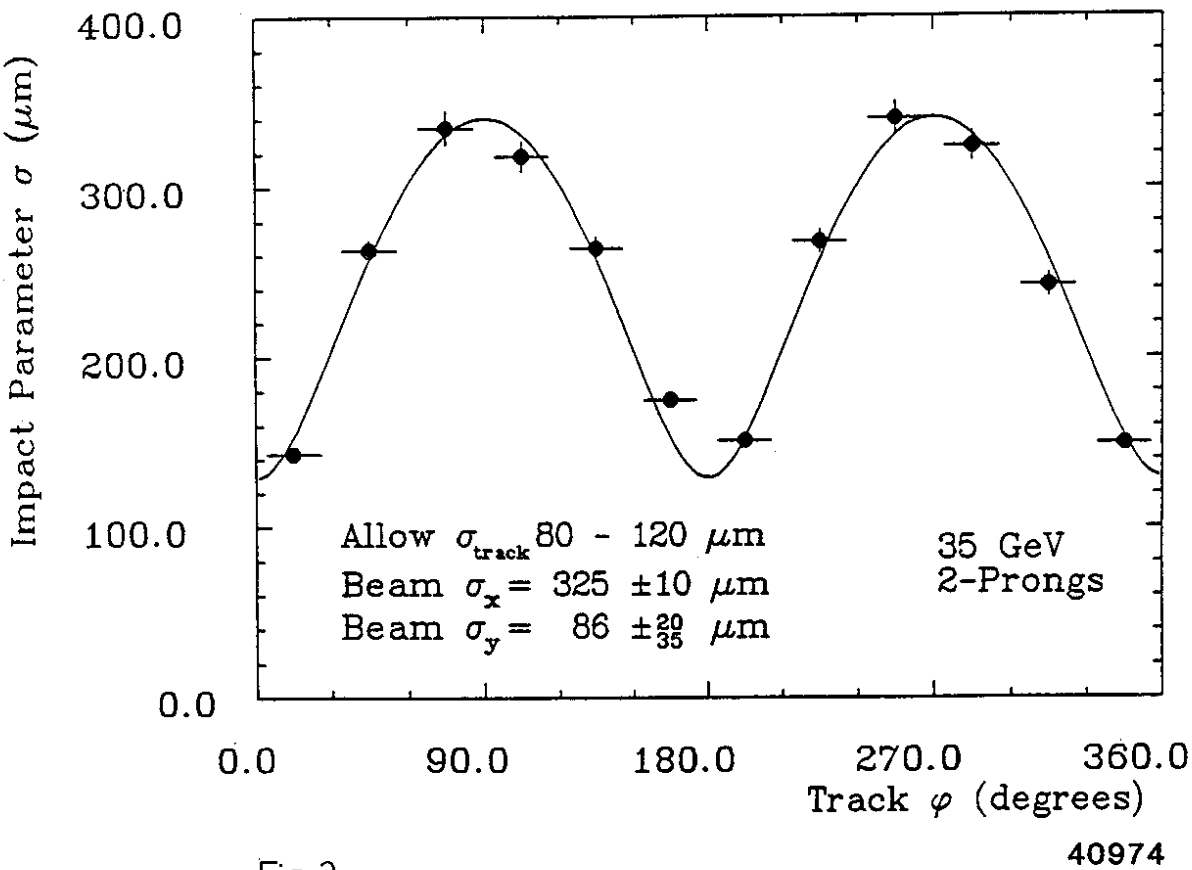

Fig. 3

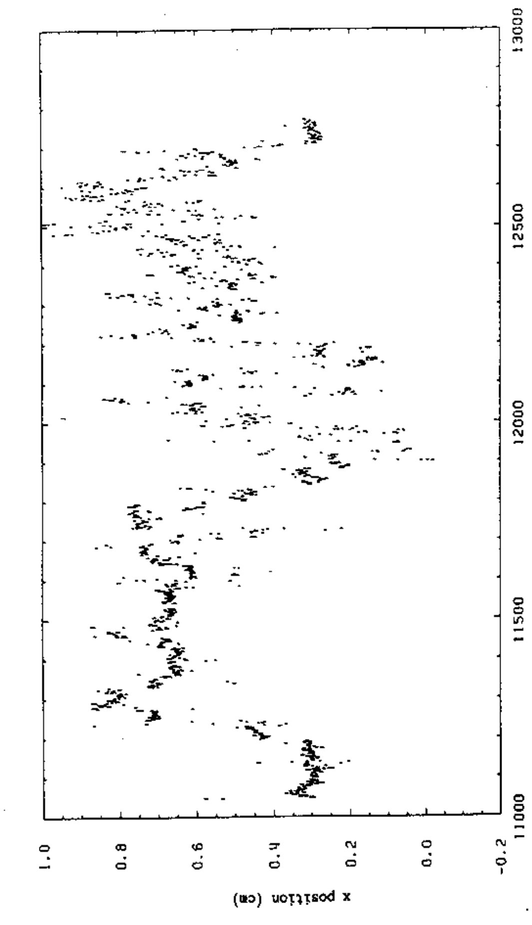

Fig.2a

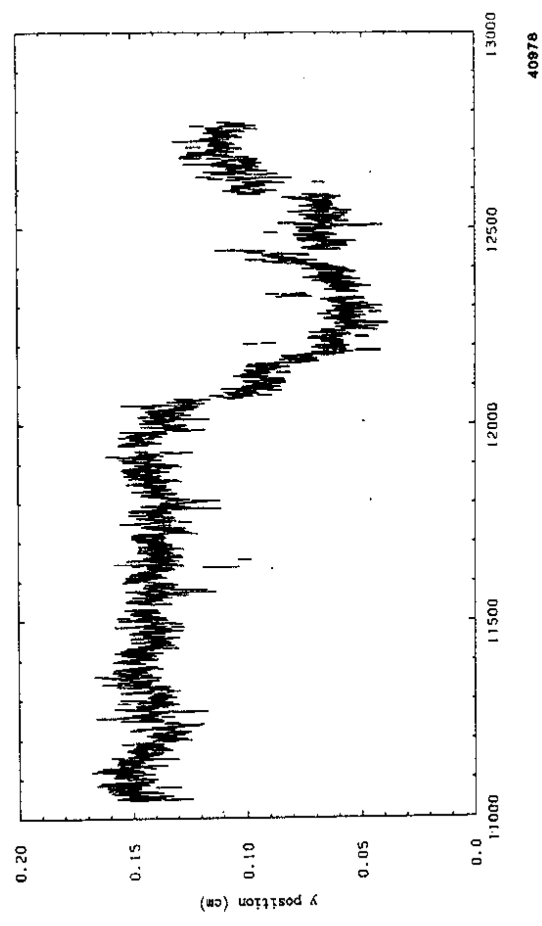

Fig.2b

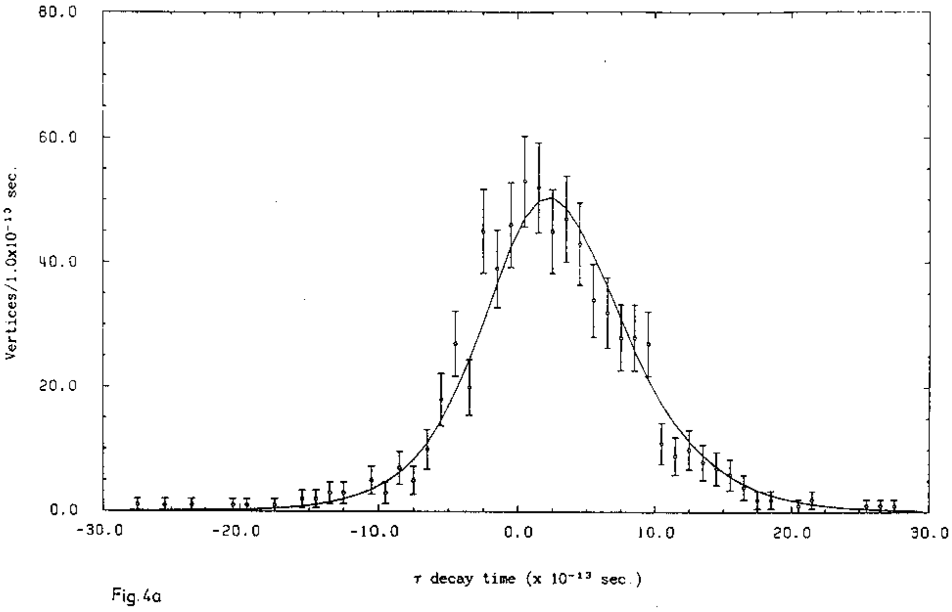

Fig.4a

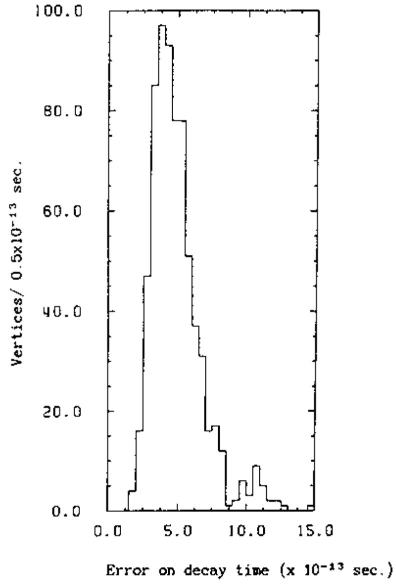

Fig.4b

40977

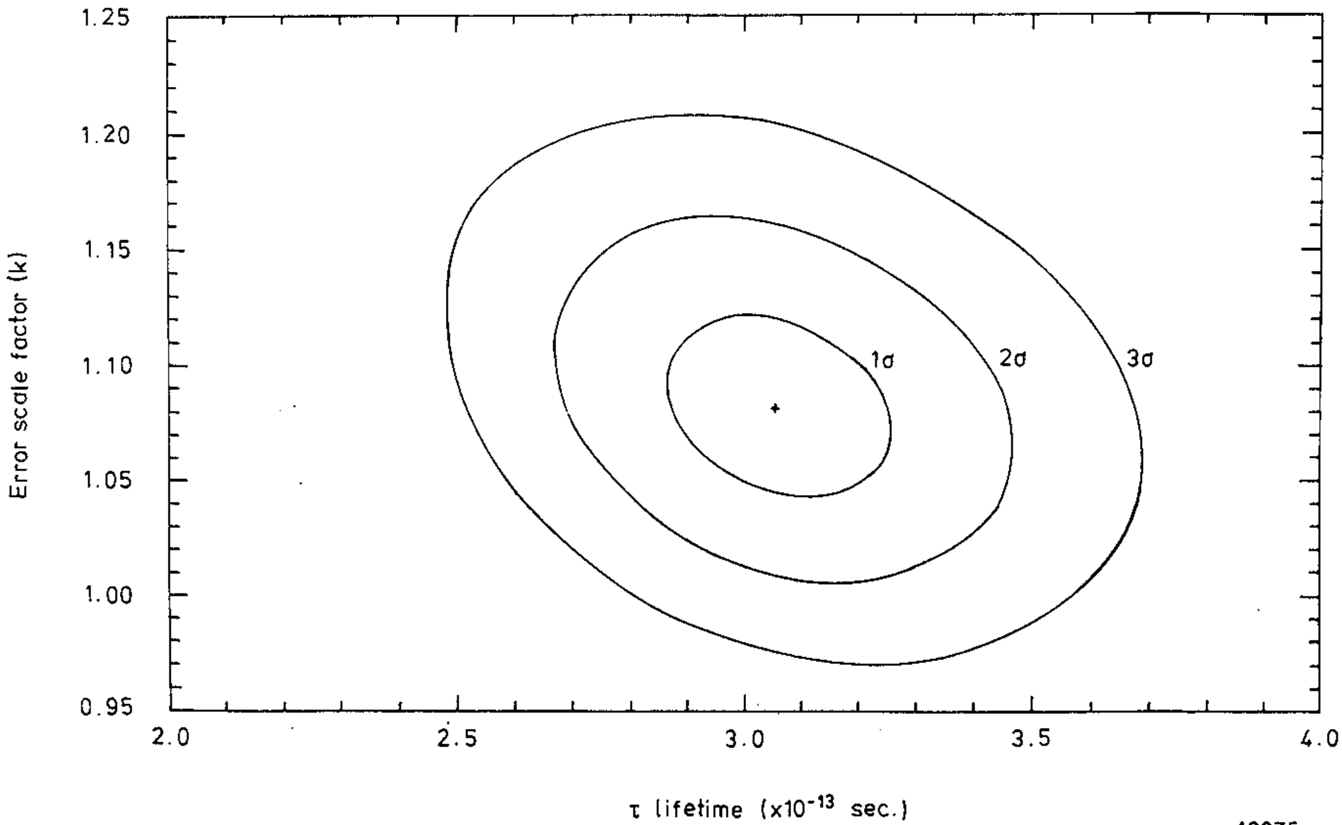

Fig.5

40975

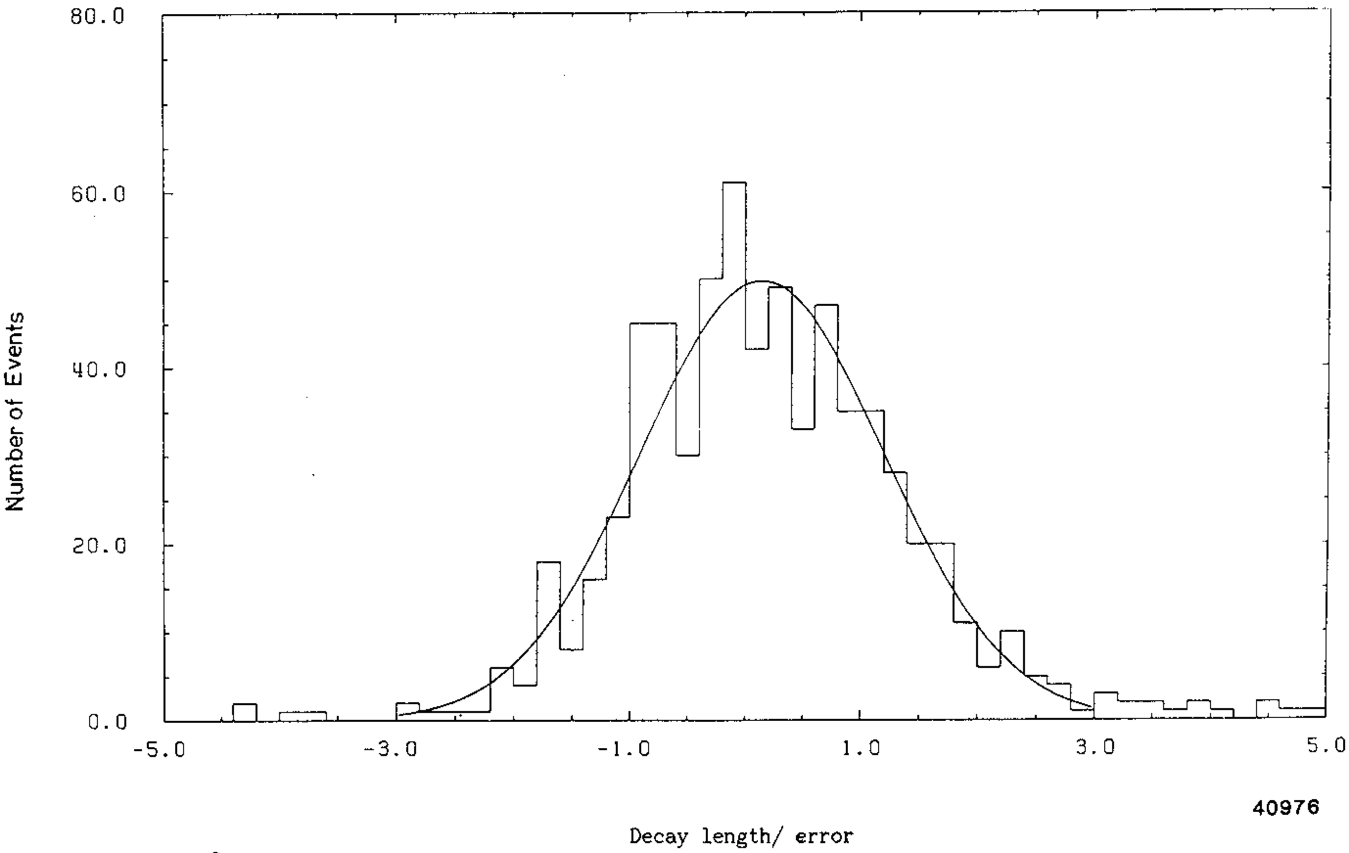
80.0
60.0
40.0
20.0
0.0
Number of Events
-5.0
-3.0
-1.0
1.0
3.0
5.0
40976
Decay length/ error

Fig. 6

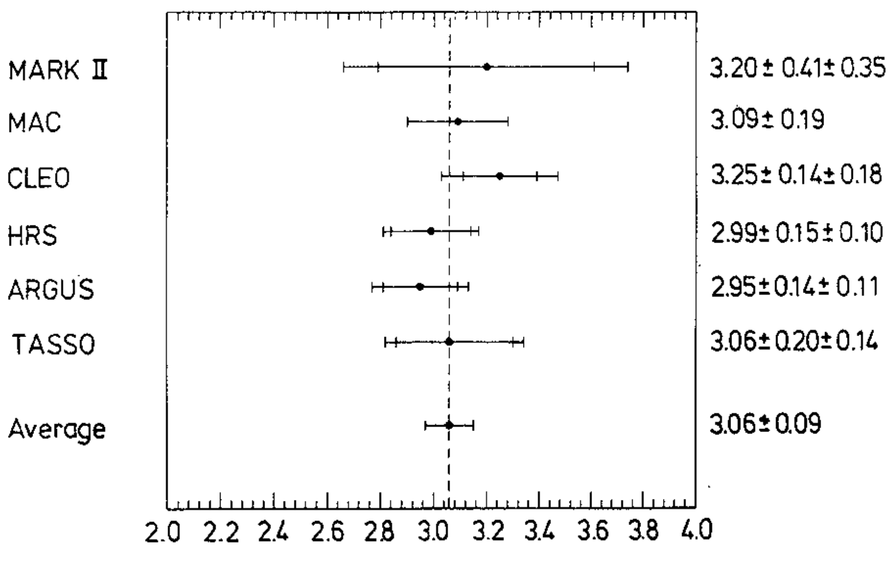
MARK II
MAC
CLEO
HRS
ARGUS
TASSO
Average
3.20 ± 0.41 ± 0.35
3.09 ± 0.19
3.25 ± 0.14 ± 0.18
2.99 ± 0.15 ± 0.10
2.95 ± 0.14 ± 0.11
3.06 ± 0.20 ± 0.14
3.06 ± 0.09
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
4.0
τ lifetime 10^-13 sec
41094

Fig. 7