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c, b, AND τ LIFETIME MEASUREMENTS IN e^+e^- INTERACTIONS*

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INTRODUCTION

Measurements of the lifetimes of weakly decaying particles let us infer the strength of the interaction responsible for their decay. Two features of these interactions have emerged from studies of the lighter quarks and leptons. First, the interactions have universal strength; and second, the weak interaction mixes the physical quark states. By measuring the lifetimes of the charmed particles, the tau lepton, and hadrons containing the bottom quark, we are testing universality in a new domain and investigating new examples of mixing.

e^+e^- annihilations are a suitable laboratory for these studies. The heavy flavors are produced in sufficient numbers for lifetime determinations and are relatively easy to identify against the light flavor background. At PEP/PETRA energies, lifetimes in the 10^{-13} to 10^{-12} s range result in average decay lengths between 100 and 1000 μ. The techniques which have been successful at measuring decay lengths in this range, notably high resolution bubble chambers and nuclear emulsion, are not easily adaptable to the e^+e^- storage ring environment, with its megahertz repetition rates, occasional beam loss, and no-trespassing zone imposed by the beam pipe. However during the past two years, several of the PEP and PETRA experiments have begun

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to probe sub-millimeter decay lengths with drift chamber techniques, and just one year ago the Mark II collaboration at PEP installed a high precision drift chamber especially tailored for lifetime studies.

These electronic measurements at e^+e^- storage rings differ markedly from the optical techniques which have provided most of our present knowledge of charmed particle lifetimes. In the first place, they generally have much lower resolution. The optical experiments generally reconstruct the decay vertex position with an uncertainty which is small compared to the average decay length being measured, so the decay length error is purely statistical, $\Delta\lambda = \lambda/\sqrt{n}$. In most of the e^+e^- experiments reported so far, the decay vertex resolution (σ) is five to ten times larger than the expected lifetime. What is measured, instead of an exponential decay distribution, is the shift of the mean of an essentially Gaussian distribution to positive decay lengths. Of course, the statistical power of the method is diluted by the large errors, $\Delta\lambda = \sigma/\sqrt{n}$ where $\sigma >> \lambda$. The second difference between the techniques comes from their very distinct systematic errors. The optical techniques have been used in high background environments where events must have finite decay lengths to be recognized as charm candidates and the efficiency for detecting decay vertices varies with decay length. In the e^+e^- experiments, it has been possible (and necessary!) to select events without reference to decay lengths. However, systematic biases may be introduced when the vertex resolution is much larger than the average decay length.

This paper will focus on measurements of the τ and D^0 lifetimes made with the Mark II vertex detector. This device, which is described below, has achieved a decay vertex resolution comparable to, instead of five to ten times greater than, the decay lengths being measured. Consequently, its statistical precision is only ~ $\sqrt{2}$ worse than the statistical limit, and the systematic errors are considerably reduced. The paper concludes with a description of lepton impact parameter measurements made by the JADE and MAC experiments which have been used to set upper limits to the B lifetime.

MARK II VERTEX DETECTOR

The Mark II vertex detector[1], Fig. 1, has been designed to optimize vertex resolution in the e^+e^- environment. It is a relatively short cylindrical drift chamber, 1.2 m long, with seven axial layers of drift cells. Four are about 11 cm from the beam line, and three at about 30 cm. It has 825 drift cells in all; the drift cell radius throughout the array is 0.53 cm. To keep multiple scattering to a minimum the chamber has been built directly outside a beryllium beam pipe 0.6% of a radiation length thick. The beam pipe serves as the inner gas seal for the chamber. The average resolution per layer in hadronic events is about 100 μ. When tracks are extrapolated to the vicinity of the interaction point, their accuracy is given by

$$\sigma(\mu) = \left(100^2 + \left(\frac{100}{P(\mathrm{GeV}/c)}\right)^2\right)^{\frac{1}{2}} ,$$

where the first term is the extrapolation error, and the second term

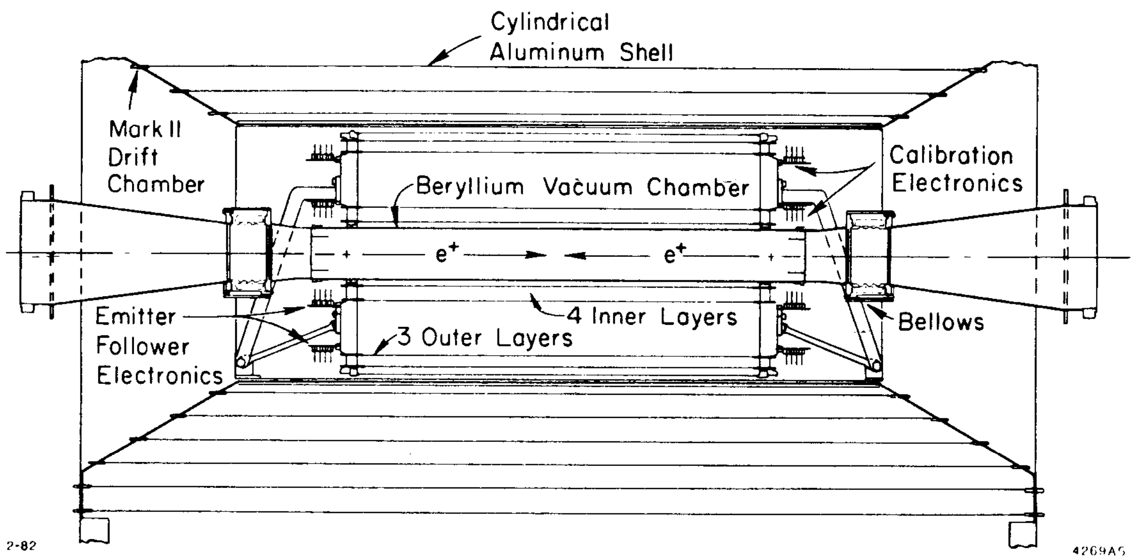

Fig. 1 Cross-section of the vertex detector as installed in the Mark II detector.

is due to multiple coulomb scattering in the beam pipe and chamber. Figure 2 shows the measured distance between the two tracks in Bhabha events after extrapolation to the origin, and it demonstrates that $\sigma_t \simeq 100\ \mu$. The chamber was installed at PEP during September, 1981 and began taking data in December, 1981. During the 1981-82 running period at PEP, an integrated luminosity of 21 pb^{-1} was accumulated at 29 GeV center-of-mass energy. Most of this data sample was used for the τ lifetime and D^o lifetime analyses presented below.

τ LIFETIME

1. Motivation. The τ lifetime provides a sensitive check of the standard model of weak interactions. The key assumption is that tau decay proceeds in direct analogy with muon decay; i.e., that the charged weak current mediating the decay has the universal Fermi strength and V-A structure, and that the tau neutrino is massless. With these assumptions, the tau lifetime can be related to the muon lifetime with two factors, one which accounts for the greatly increased phase space in the decay, and the other for additional decay channels:

$$\tau_\tau = \tau_\mu \cdot \left(\frac{m_\mu}{m_\tau}\right)^5 \cdot B\ (\tau \rightarrow e\nu\bar{\nu})$$

Experimentally[2] $B(\tau \rightarrow e\nu\bar{\nu}) = 17.6 \pm 1.1\%$, so $\tau_\tau = 2.8 \pm 0.2 \times 10^{-13}$ s, where the error reflects the uncertainty in the electronic branching ratio.

How might this prediction fail? The most fundamental failure would be that the tau coupling strength is not universal. This

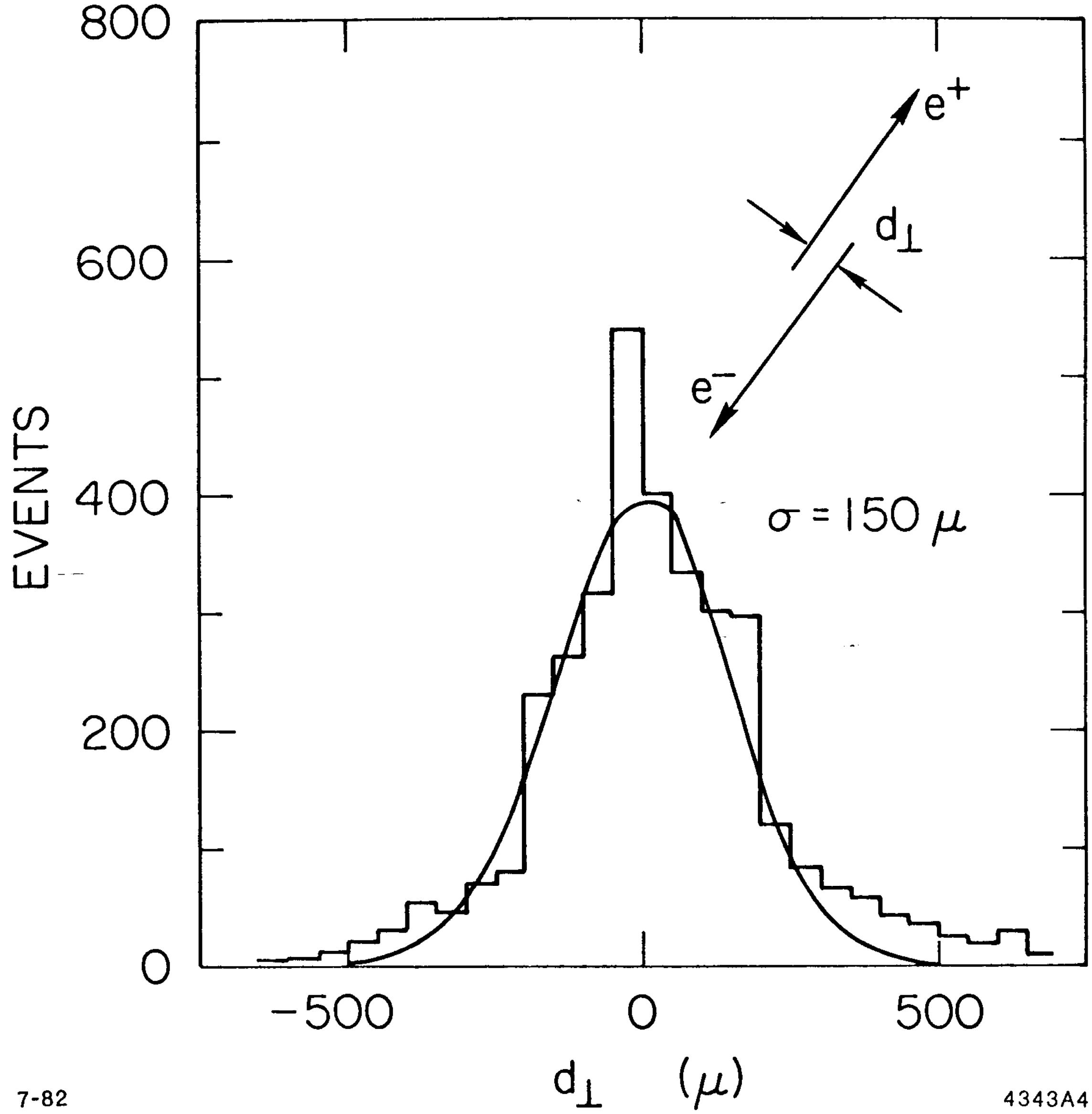

Fig. 2 Distance between tracks in Bhabha events, measured at the interaction point.

occurs, for example, in a model of Li and Ma[3] in which each lepton generation is associated with a unique gauge group -- hence unique weak bosons and couplings. The model predicts an increased τ lifetime, a proliferation of gauge bosons, and observable B^o-$\bar{B}^o$ mixing. Mixing among the quark generations in hadron decays leads to the apparent violation of universality, and of course mixing among the lepton generations would have the same effect. For example, if the tau neutrino mixed with a fourth generation neutral lepton whose mass was greater than the tau mass, the decay rate would be suppressed[4]. More trivially the tau lifetime would be extended if the tau neutrino were massive enough to limit significantly the phase space of the decay. There are other mechanisms that would alter the lifetime prediction. A charged Higgs with rather artificial couplings could increase the decay rate slightly[5]. If the tau were spin 3/2, its decay rate need not be canonical[6]. In contrast to predictions for the hadron lifetimes, where strong-interaction effects, quark mass uncertainties, and quark mixing complicate the situation, the τ lifetime prediction depends on only a few, fundamental assumptions about the weak interactions. If it is wrong, some interesting new physics is indicated.

2. Method. Tau leptons are pair-produced in e^+e^- annihilations, so each tau has the known beam energy. Thus we can measure the lifetime by determining the average decay length of the taus. At PEP energies, E_{cm} = 29 GeV, it is expected to be about 700 μ.

The decay length can be measured when the tau decays in the three-charged-prong topology. It is simply the distance between the production point, i.e., the beam position, and the position of the decay vertex. This same technique has been exploited by several PEP and PETRA experiments[7-10].

3. Event Selection. Tau production at PEP/PETRA energies is distinctive: low multiplicity, low mass, back-to-back jets are produced, which are easily distinguished from higher multiplicity hadron production. We select events in which at least one of the taus has decayed in the three-charged prong topology and the total charge of the prongs is zero. We require the three particle invariant mass to be in the range $0.7 < m_{3\pi} < 1.5$ GeV/c^2, and, to reject tau pairs produced by two-photon process, we further demand that the total energy in the event be at least one fourth the center-of-mass energy and the three-pion energy exceed 3 GeV. All three tracks must be well-measured in both the main drift chamber and the vertex detector. Figure 3a shows such an event in the Mark II detector. Figure 3b gives an enlarged view of the vertex detector for this event, and Fig. 3c shows a much enlarged view of the decay vertex in the vicinity of the interaction point.

4. Decay Length. The decay length is determined once we have measured the beam position, the decay vertex position, and the tau direction.

The rms beam size at PEP is 500 μ horizontally and about 50 μ vertically. The average beam position is remarkably stable from

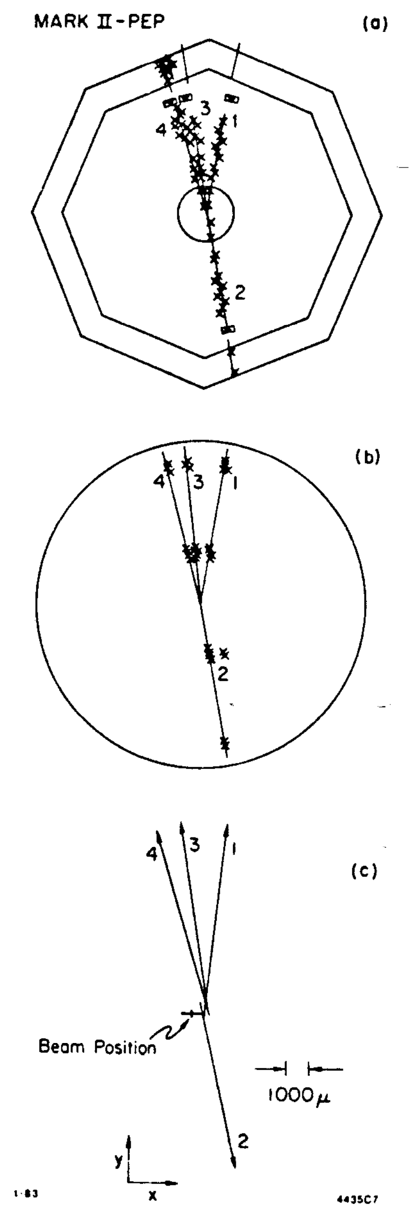

Fig. 3 (a) $e^+e^- \to \tau^+\tau^-$ as seen in the Mark II detector at PEP;
(b) close-up of the same event in the vertex detector;
(c) extreme closeup of the same event showing particle trajectories extrapolated to the vicinity of the interaction point.

one fill to the next. Over the course of the entire experiment the horizontal beam position varied less than 2 mm and the vertical beam position, 0.5 mm. We measured it by finding the average intersection point for an ensemble of well-measured tracks. As a cross check, we have compared this determination of the beam position to the vertex position measured in hadronic events. Figure 4 shows that these methods agree. The width of the Δx distribution is consistent with the known beam size, and the width of the Δy distribution is consistent with our vertex resolution. This demonstrates that the beams are stable.

The decay vertex position and its error ellipse are determined from the three pion trajectories and their associated errors with a chi-square minimization procedure. We exclude events with a vertex chi-squared per degree of freedom greater than 6. The best estimate for the projected decay length is then given in terms of the decay vertex position relative to the beam position (x_v, y_v), the sum of the beam and vertex error matrices (σ_{ij}), and the τ direction cosines (t_x, t_y) by the following expression:

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

The tau direction is accurately approximated by the direction of the 3π system. Then the decay length is

$$\ell = \frac{|\bar{p}_{3\pi}|}{p_{3\pi}^z} \ell_p \quad ,$$

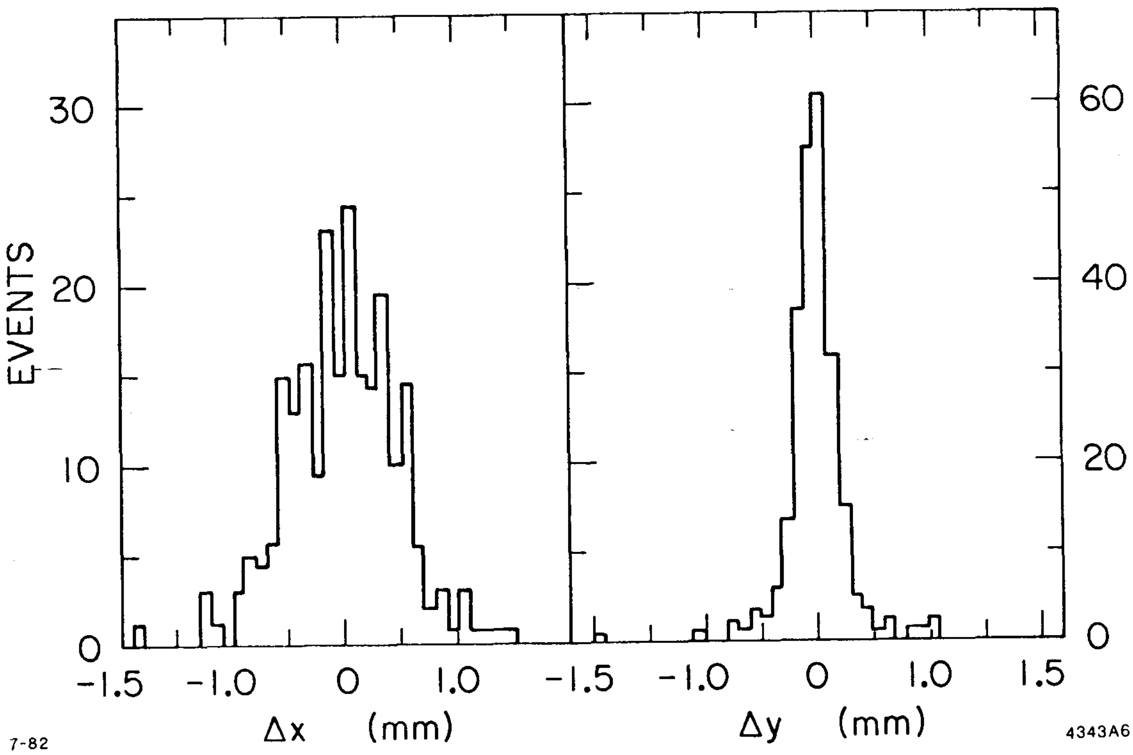

Fig. 4 Horizontal and vertical hadronic vertex positions relative to the beam position. Only those runs with tau decays are shown.

where $\bar{p}_{3\pi}$ is the total momentum of the three pion system.

Figure 5 shows the calculated error in the decay length, which depends on the opening angles and orientation of the decay, the tracking errors, and the beam size. In contrast to previous experiments, the average uncertainty in the decay length is comparable to, not five to ten times greater than, the expected decay length. Consequently, the statistical power of the experiment is improved by roughly this same factor, and the measurement bias is significantly reduced.

The measured decay lengths are shown in Fig. 6, where we have included only those events with decay length errors less than 1.5 mm. The mean of the distribution is obviously positive and its shape is asymmetric. We fit the distribution with a maximum likelihood technique which takes the decay length error into account event-by-event. The fitting function is the convolution of the Gaussian decay length error with an exponential decay distribution. We find that the average decay length is 710 ± 120 μ.

5. Checks and Corrections. We have checked our tracking, vertexing, and fitting programs with simulated data generated by Monte Carlo techniques. Roughly 1000 decays were generated for each of three lifetimes, $\tau_\tau = 0$, $\tau_\tau = 2.8 \times 10^{-13}$ s, and $\tau_\tau = 5.6 \times 10^{-13}$ s; they were then analyzed with the same programs used for actual data analysis. The simulated data are shown in Fig. 7. The zero-lifetime distribution is quite symmetric and centered near zero decay length. The nominal lifetime distribution

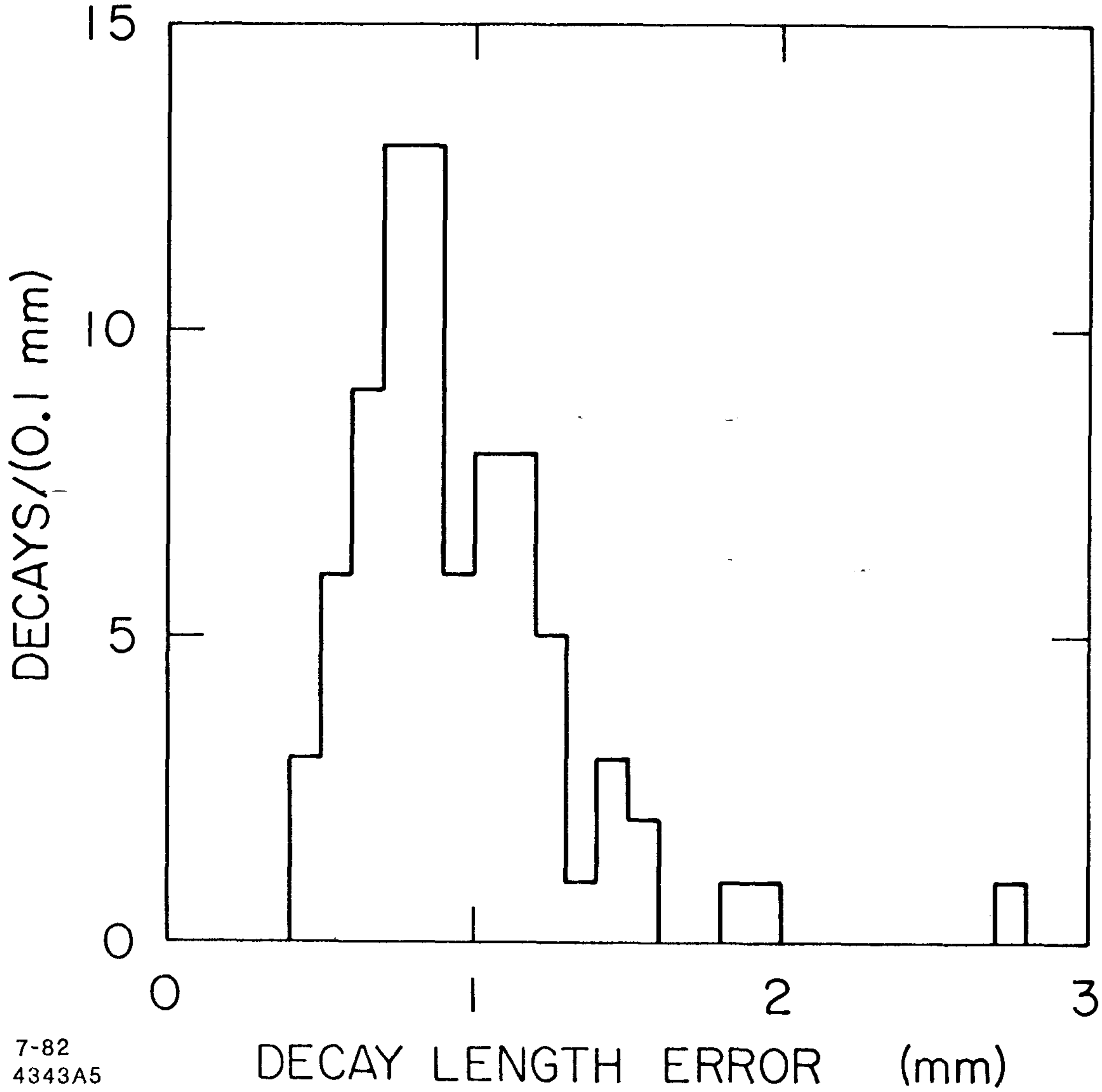

Fig. 5 Calculated error in the decay length.

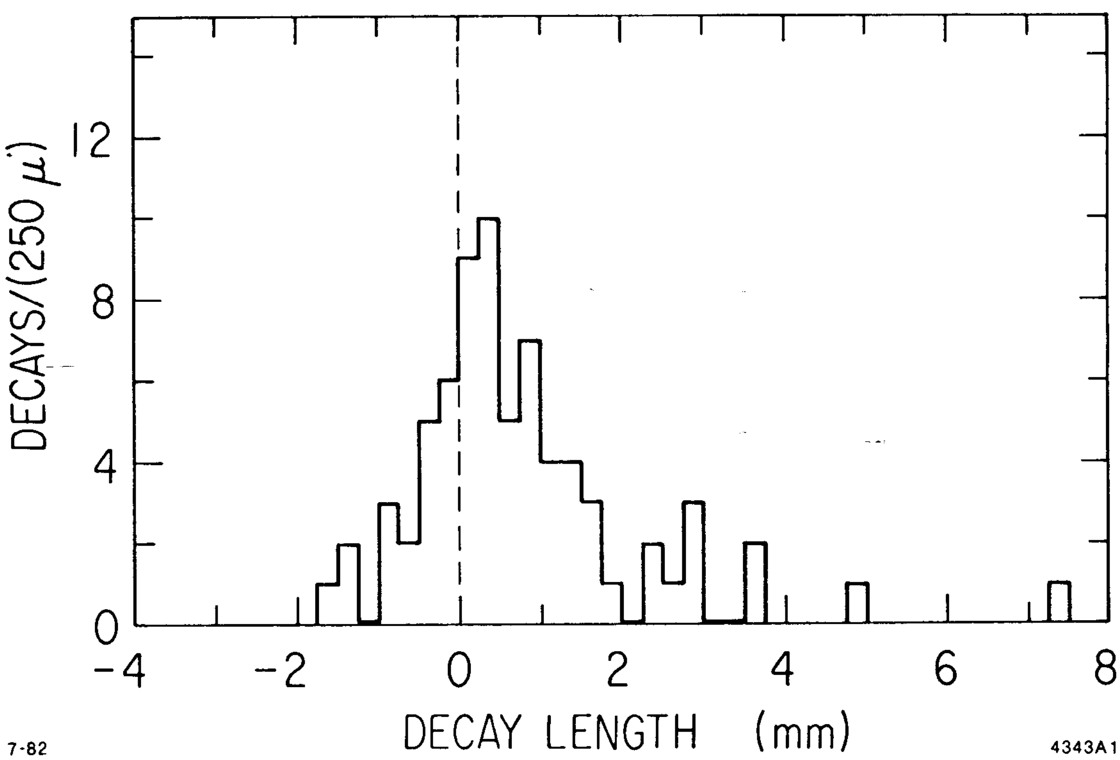

Fig. 6 Measured decay lengths.

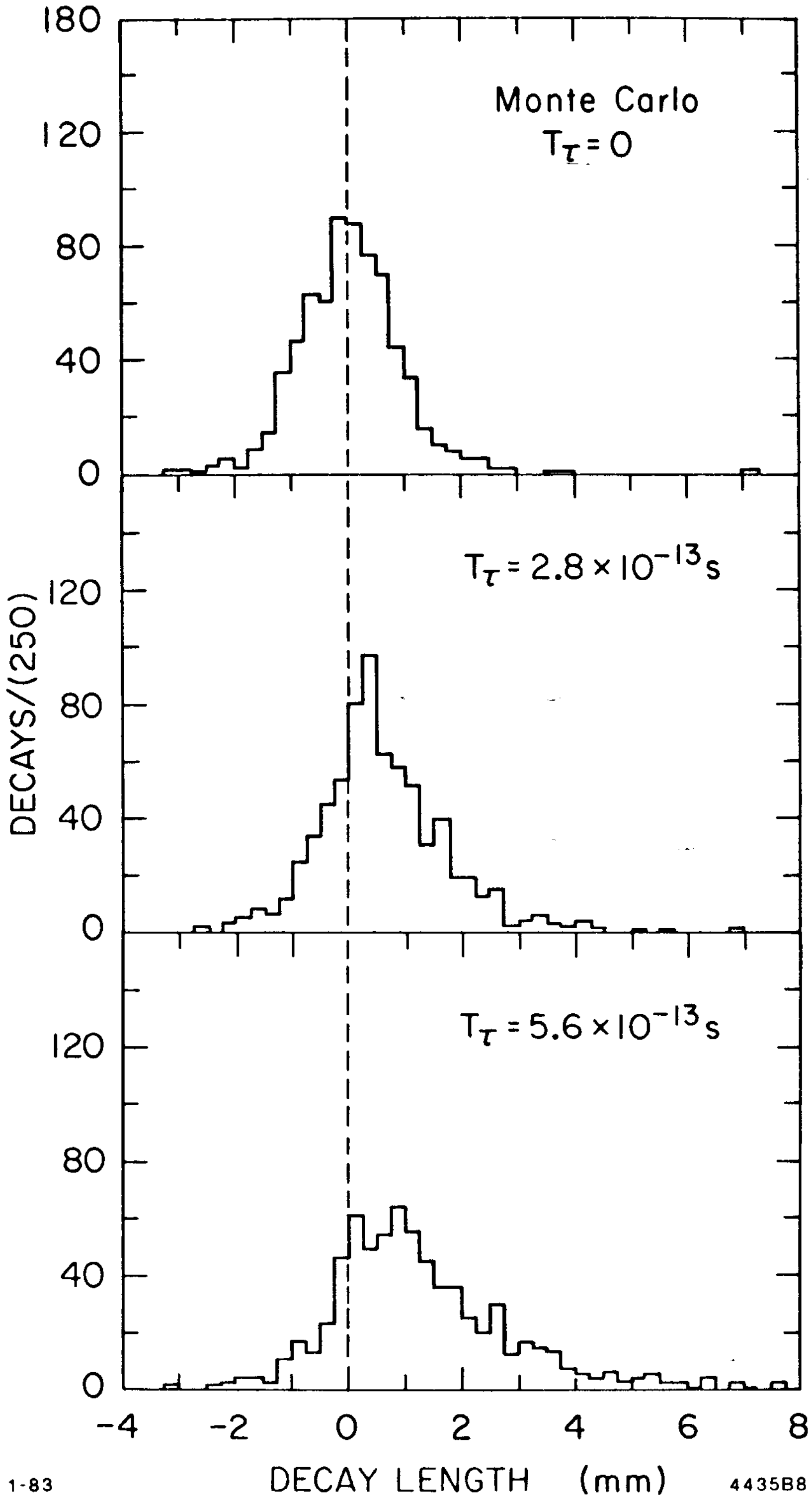

Fig. 7 Monte Carlo simulated decay length distributions for τ_τ = 0, 2.8 x 10^{-13} s, and 5.6 x 10^{-13} x.

nearly fits the data and is clearly shifted to positive decay lengths. The two-times nominal lifetime distribution shows an unmistakable exponential tail. Table I summarizes the average decay lengths generated for each of the three lifetimes, and the decay length determined by fitting the simulated data. This checks that our analysis procedure is reliable to the 50 μ level of accuracy.

Table I
Monte Carlo Simulation

Lifetime (10^{-13} s)	Average Decay Length Generated (μ)	Average Decay Length Fit (μ)
0	0	45 ± 25
2.8	644	605 ± 35
5.6	1338	1240 ± 50

We performed an additional check by analyzing pseudo-tau decays in hadronic events. Three-particle combinations were chosen in hadronic events to mimic the properties of the three-pion tau decays as accurately as possible. The average "decay length" for these combinations was 250 ± 40 μ; our hadron Monte Carlo events gave a decay length of 275 ± 50 μ. The presence of charm decays explains the finite decay length, and the Monte Carlo correctly simulates the data.

We studied systematic effects by re-analyzing the data with different assumptions about the beam position, beam width, resolution, and fitting function. The observed variations lead us to assign a systematic error of ± 150 μ to the decay length.

Using a Monte Carlo calculation, we estimate that 10% of our tau candidates are hadrons. This leads to a + 50 μ correction in the average decay length. Initial state radiation lowers the average tau energy from its nominal 14.5 GeV to 13.8 GeV.

6. Results and Conclusions. After correcting for hadron contamination and initial state radiation, we find $\tau_\tau = 3.31 \pm 0.57 \pm 0.60 \times 10^{-13}$ s, where the first error is the statistical error and the second is the systematic. Our measurement is compared to the other measurements which have appeared in the literature or were presented to the XXI International Conference of High Energy Physics, Paris, France in Table II. The number of decays studied and the average decay length error are also shown for comparison.

Table II

Experiment	Number of Decays	Average Decay Length Error (mm)	τ_τ (10^{-13} s)
TASSO[7]	599	10	0.8 ± 2.2
MARK II[8]	126	4	4.6 ± 1.9
MAC[9]	280	4	$4.1 \pm 1.2 \pm 1.1$
CELLO[10]	78	6	$4.7 \pm^{3.9}_{2.9}$
MARK II Vertex Detector	71	0.9	$3.31 \pm .57 \pm .60$

All of the measurements are consistent with the expected lifetime. The present experiment confirms that the tau couples to the charged weak current with universal strength within the present statistical and systematic errors,

$$g_\tau/g_e = 0.92 \pm 0.086 \pm 0.090 \ .$$

If we assume that the coupling has the universal strength, we can set a limit on the mass of the tau neutrino. Figure 8 shows how the lifetime varies as a function of the tau neutrino mass[11] along with the 90% confidence level upper limit set by this measurement. We find $m_{\nu_\tau} < 0.49$ GeV/c^2, which is compatible with the .25 GeV/c^2 limit deduced from the shape of the decay lepton spectrum[12]. There is obviously little sensitivity to neutrino masses below about 150 MeV/c^2 with this method. We can also set a limit on how much the tau neutrino mixes with a heavy neutral lepton (N_o) whose mass exceeds the tau mass. The mixing angle ε is defined by the relation

$$\nu_\tau \equiv \nu'_\tau \cos \varepsilon + N_o \sin \varepsilon \quad ,$$

where ν_τ and N_o are the mass eigenstates and we've assumed there is only mixing with this heavier generation. At the 90% confidence limit $\sin \varepsilon < 0.65$. Clearly the present data do not exclude significant mixing with other lepton generations.

The prospects for improved precision and accuracy in measurements of the τ lifetime are good. An integrated luminosity of 100 pb^{-1} at PEP/PETRA energies would allow a statistical precision in the 5 to 10% range. Holding and believing the systematic errors to that level will be challenging until the vertex resolution is significantly smaller than the decay length. The Z^o should be a prolific source of $\tau\bar{\tau}$ pairs, so high statistics determinations of the τ lifetime will await LEP and the SLC. The SLC, with its micron-sized beam, is an especially interesting τ source.

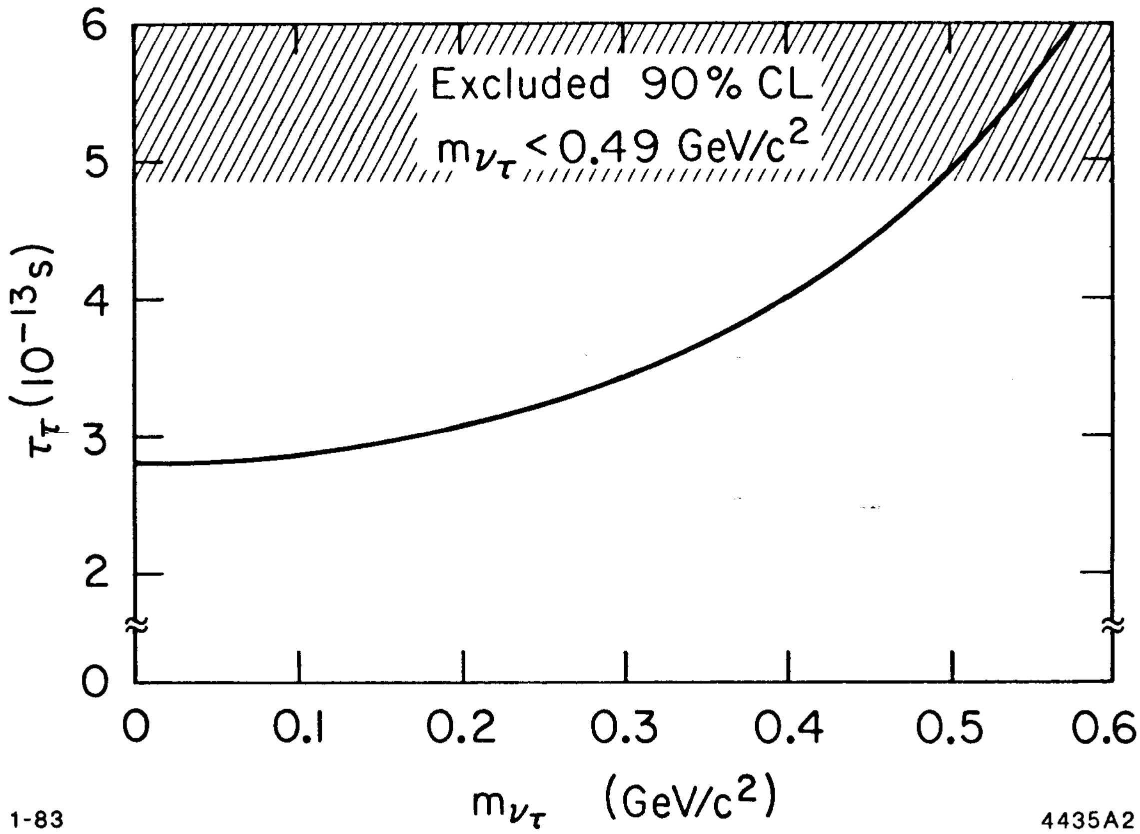

Fig. 8 Variation of the τ lifetime with the mass of the τ neutrino.

D^o LIFETIME

There has been a flurry of experimental activity, and considerable experimental as well as theoretical confusion concerning charmed particle lifetimes in the past few years. As Kalmus[13] reported to the Paris conference, the situation seems to be stabilizing as follows: The D^o lifetime is about 4×10^{-13} s, about half the D^+ lifetime of 9×10^{-13} s. As Fig. 9 shows, however, the experimental situation for the D^o lifetime measurements is still a little rocky. All the experiments suffer from low statistics and possible systematic biases.

In the standard model, charmed hadron decays are expected to be unsuppressed (i.e., mixing with the heavier flavors is presumed to be small), so the decay rate is fixed by the quark mass. Although this idea predicts the correct magnitude for the charmed lifetimes, it does not account for the observed lifetime differences, indicating that free quark decay is not the sole decay mechanism. The pattern of charmed hadron lifetimes will help elucidate these decay mechanisms and hopefully serve as a guide to the decays of heavier flavors.

We have measured the D^o lifetime with the Mark II vertex detector using a sample of D^o's which had been cleanly identified by the main tracking chamber. The measurement differs significantly from previous measurements which used optical techniques in that (i) events are selected independently of the observed decay length, and (ii) the vertex resolution is comparable to, not significantly

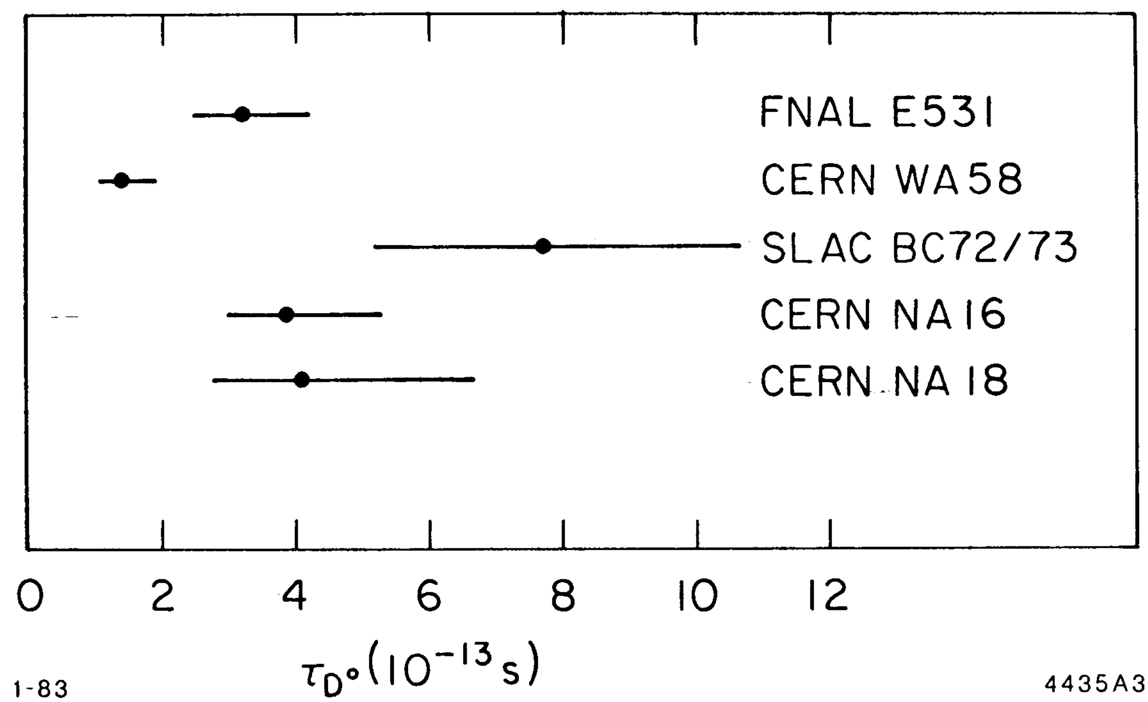

Fig. 9 World data on D^0 lifetime measurements taken from ref. 13.

smaller than, the average decay lengths. Like the others, our measurement suffers from low statistics. An integrated luminosity of 17 pb^{-1} gave seven well-measured D^o decays.

1. Event Selection. The clean event sample comes about by selecting D^o's from D^* decays. The technique is as follows. We first construct a two-particle invariant mass, arbitrarily assigning one particle the pion mass and the other the kaon mass. We select neutral combinations with $1.76 < m_{K\pi} < 1.96$ GeV/c^2 as D^o candidates, and consider the possible three-particle combinations, $m_{K\pi\pi}$. Figure 10 shows the mass difference, $m_{K\pi\pi} - m_{K\pi}$, displayed with two different cuts on the fractional energy of the three-particle combination, $z = E_{D^*}/E_{beam}$. When $z > 0.4$, one sees a clustering at .145 GeV/c^2 in the mass difference, which corresponds to $m_{D^{*+}} - m_{D^o}$. For the lifetime analysis below, we select events with $z > 0.6$. They seem to be free of background and so provide an ideal sample for study. This high momentum cut also makes it unlikely that these D^*'s have originated from B decays[14].

2. Lifetime Measurement. The decay vertex is determined by vertexing the K and π from the D^o. The decay length is then determined with the same technique used in the tau analysis above. The projected decay length is corrected using the measured D^o direction to find the actual decay length. It, in turn, is converted to the proper time using the measured D^o momentum. The average decay length is about 500 μ, and the average vertex error about 700 μ. Figure 11

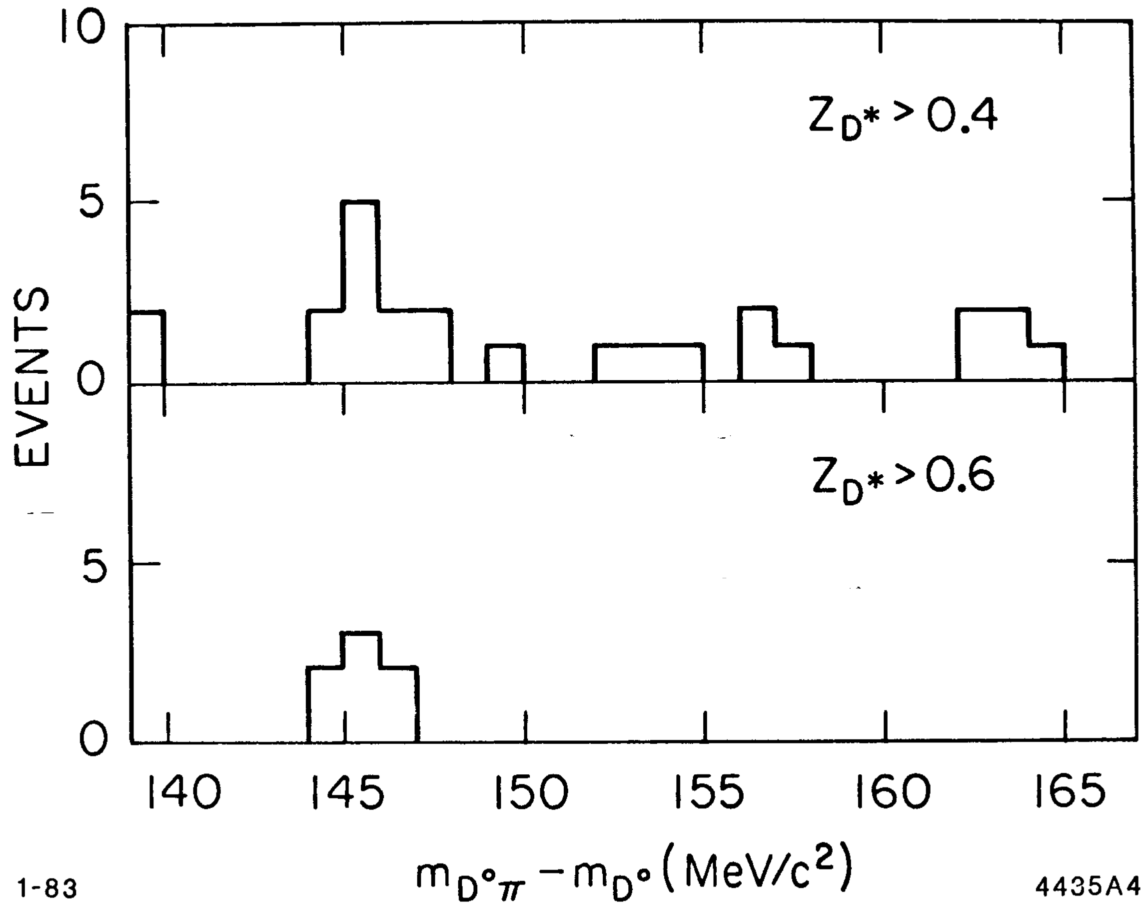

Fig. 10 $D^o\pi^\pm$ - D^o mass difference for D^o candidates decaying into $K\pi$.

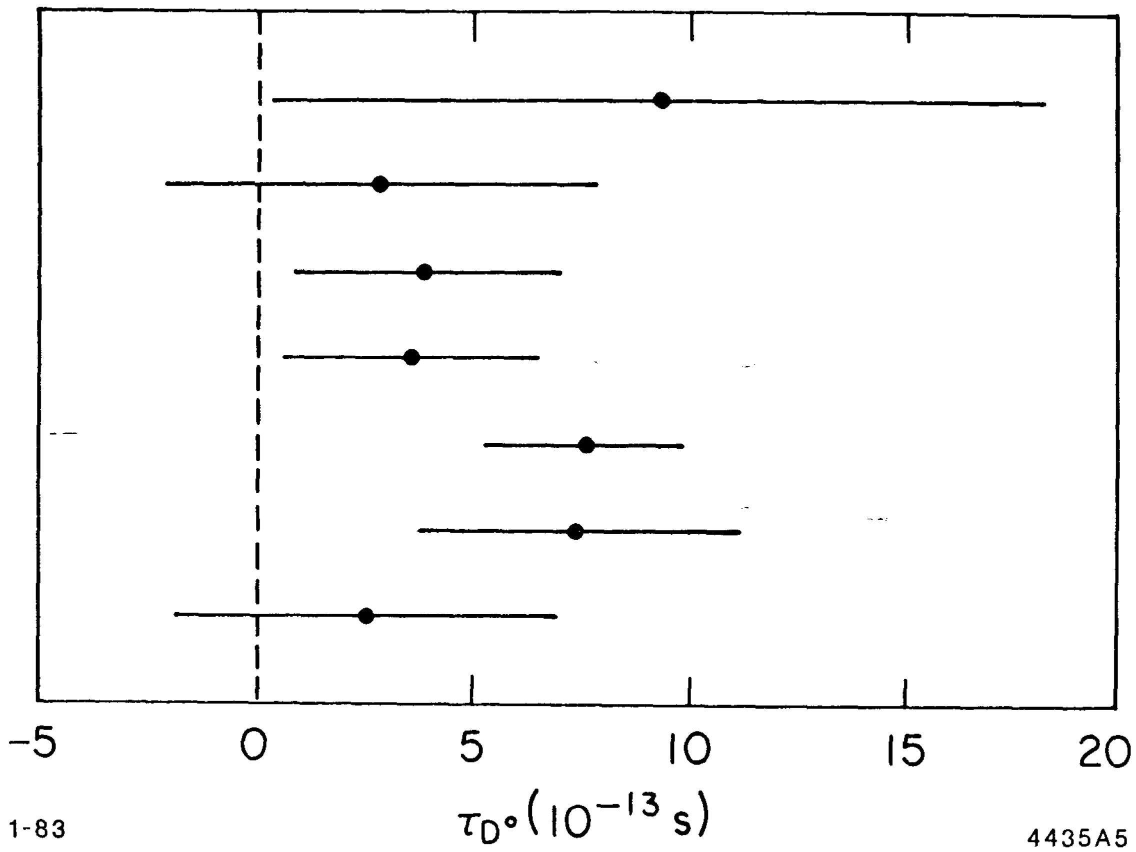

Fig. 11 Measured proper times for the seven D^0 events.

shows each of the 7 measurements with its error. As in the τ measurement, we perform a maximum likelihood fit using the convolution of a Gaussian resolution function with an exponential decay distribution as a fitting function. We have checked the analysis procedure on Monte Carlo data and considered its sensitivity to errors in the beam position, the resolution function, etc. We find the D^o lifetime to be $\tau_{D^o} = 3.7 \pm {}^{2.5}_{1.5} \pm 1.0 \times 10^{-13}$ s, where the first error is statistical and the second systematic. This result is in agreement with the current world average. The experiment is continuing, so we hope to increase the statistical significance of this measurement.

LIMITS ON THE B MESON LIFETIME

If their decays were not suppressed, the hadrons containing the b quark would be expected to decay with a lifetime

$$\tau^o{}_B \sim \tau_\mu \cdot \left(\frac{m_\mu}{m_b}\right)^5 \cdot \frac{1}{9} = 10^{-15} \text{ s} .$$

The (qualitative) factor 9 comes from the number of available final states. The B meson lifetime is expected to be longer, however, since the decay is suppressed by the presumably small mixing between the second and third quark generations. The B meson lifetime thus gives a measure of the quark mixing, at least if one assumes universal weak coupling strength. Several authors[15] have related the B lifetime to the quark mixing angles. Gaillard and Maiani express the lifetime in terms of the unsuppressed lifetime as

$$\tau_B = \left[\frac{9\tau_B^o}{2.75\ \sin^2\gamma + 7.69\ \sin^2\beta - 5.75\ \sin^2\beta\ \sin^2\gamma - .25\ \sin^4\gamma}\right]$$

In this parameterization, the relevant elements of the mixing matrix are $U_{ub} \equiv \sin\beta$ and $U_{cb} \equiv \sin\gamma\cos\beta\ e^{i\delta}$, with δ a phase factor. The numerical factors account for the variations in phase space among the various decay channels. Using constraints on the mixing parameters from β decay and the K_L^o/K_s^o mass difference, the same authors predict

$$\tau_B \geq 0.3 \times 10^{-13}\ \mathrm{s}\ ,$$

which would imply decay lengths at PEP/PETRA energies $\geq 10\ \mu$.

1. Lepton Impact Parameter. Two experiments have obtained upper limits for the B lifetime by measuring the average impact parameter of energetic muons. Events are selected which have high mass jets and an identified high-momentum muon. These events are almost entirely due to charm and beauty production. Using the thrust axis as an estimate of the B meson direction, a signed impact parameter is determined from the lepton trajectory and the known beam position as shown in Fig. 12. In the limit where the parent hadron velocity and the velocity of the muon in both the parent frame and the lab frame are relativistic, the distribution of impact parameters becomes Lorentz invariant and is a measure of the lifetime of the parent. Let the impact parameter be Δ. Then the unprojected distribution is given[16] by

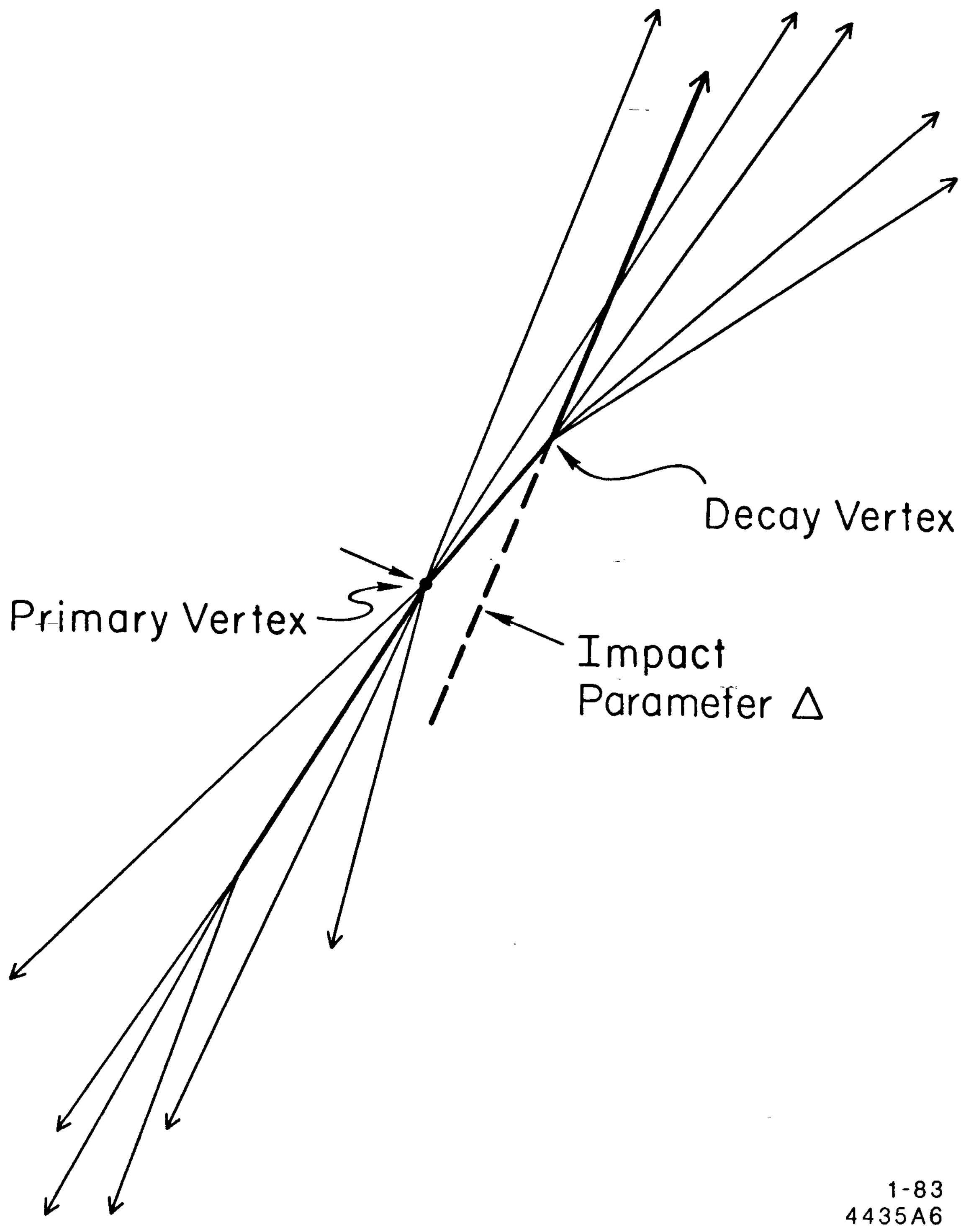

Fig. 12 Lepton impact parameter.

$$\frac{dn}{dy} = \int_0^{\infty} \frac{2yz^2 \ e^{-z} \ dz}{(z^2 + y^2)^2} \quad ,$$

where $y = \Delta/c\tau$. The distribution, which is graphed in Fig. 13, has a mean value $\bar{y} = \pi/2$. In practice, the projected distribution is measured, and its shape is somewhat distorted by event selection and particle identification cuts. The JADE group finds for their event cuts that

$$\bar{\Delta} = 200 \ \mu \times \left(\frac{\tau_B}{10^{-12} \ s} \right) .$$

In addition to this procedure, the MAC experiment also measures the average displacement of the jet vertex from the beam position in a B-enriched sample of events.

2. Results and Comments. The upper limits obtained are as follows. The JADE experiment finds $\tau_B < 1.4 \times 10^{-12}$ s and the MAC experiment finds $\tau_B < 3.7 \times 10^{-12}$ s, both limits at the 95% confidence level. Thus there is as yet no evidence for a finite B lifetime, let alone Cabibbo suppression in B decays.

Several complications enter these analyses. The selection of events is model and Monte Carlo dependent, the ratio of leptons from charm to those from bottom is imperfectly known, and the estimation of the primary vertex in an event which presumably has secondary and tertiary vertices is problematical. What is measured in such studies is, of course, a mix of lifetimes from charged and neutral, charmed and beautiful mesons and baryons. Even so, the technique shows promise. As knowledge of bottom and charm production and

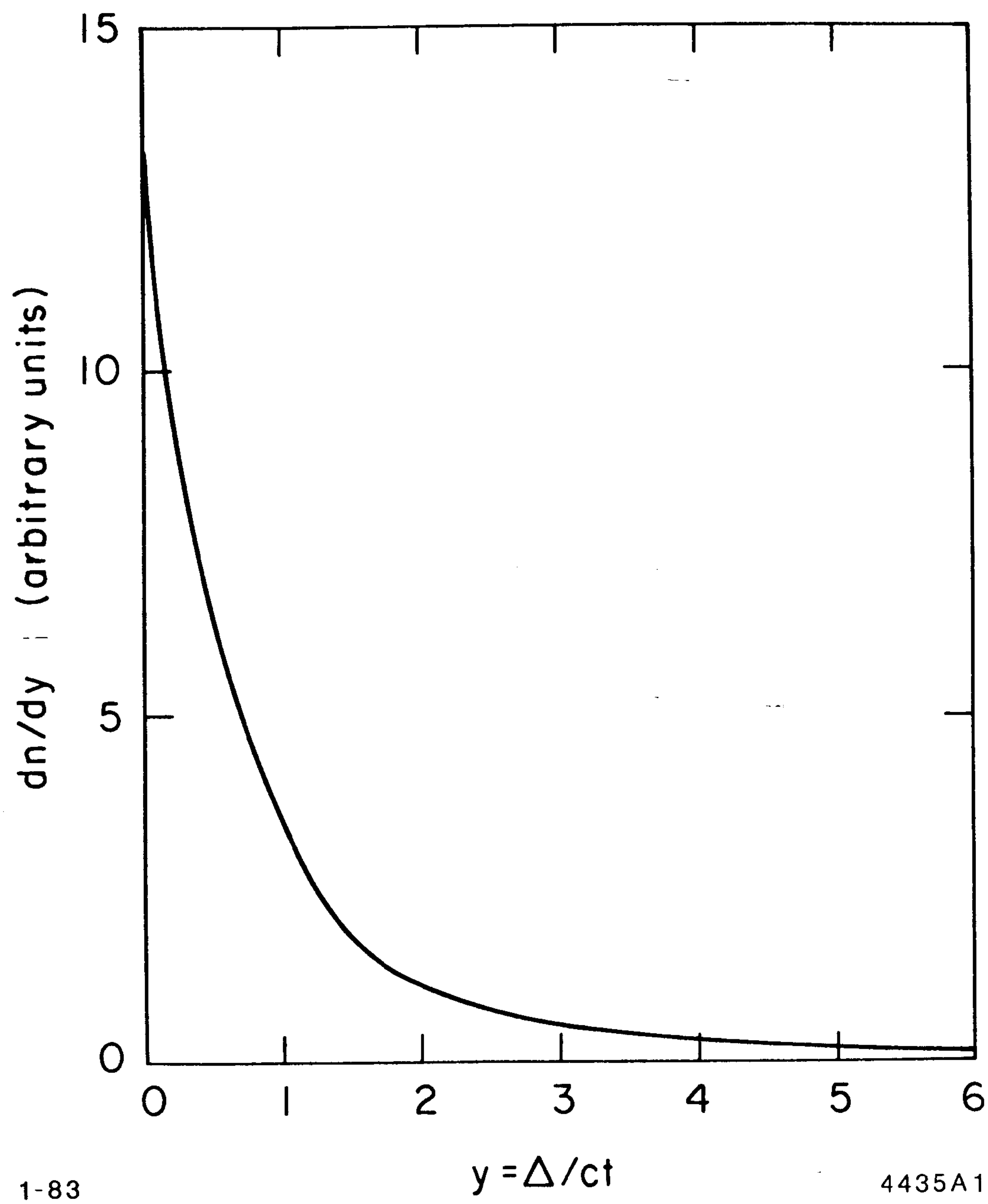

Fig. 13 Unprojected distribution of impact parameters from ref. 16.

semi-leptonic decay is refined, the results will lose their model dependence. Higher resolution devices will permit better estimates of the primary vertex, and more complicated analyses can separate charm and beauty effects.

CONCLUSIONS

Experiments at e^+e^- storage rings have successfully measured the τ and D^o lifetimes and set interesting limits on the B lifetime. So far, the conventional wisdom has prevailed. The τ lifetime is consistent with prediction; there is no sign (but little sensitivity) of a violation of universality. The charmed particle lifetimes are roughly as expected, but richer in their phenomenology than anticipated. The B lifetime is still unknown.

The experimental art is developing rapidly. Several experiments have by now installed vertex detectors. Measurements of charmed particle lifetimes from e^+e^- experiments will complement the work that has been done at fixed target machines. Measurements of τ and B lifetimes may be the exclusive province of e^+e^- experiments for the next few years. Significant improvements in these measurements await higher resolution tracking devices, positioned closer to the interaction point, and larger data samples.

ACKNOWLEDGEMENTS

My colleagues in the Mark II collaboration collected and processed the data reported here in record time. Special mention must go to Dan Amidei, Nigel Lockyer, and George Trilling for their efforts in bringing the vertex detector into operation and their help with the τ lifetime analyses. The D^0 analysis was done by Larry Gladney, Gerson Goldhaber, and John Yelton.

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