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LIFETIME MEASUREMENTS IN e^+e^- INTERACTIONS

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LIFETIME MEASUREMENTS IN e^+e^- -INTERACTIONS

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INTRODUCTION

Lifetime measurements are of considerable interest in particle physics, since they provide a direct way of inferring the strength of the interaction responsible for the decay; in particular the lifetime of charmed and bottom hadrons is, together with the branching ratios, of fundamental importance for understanding the weak decays of heavy quarks.

In these lectures I will review the recent results on the lifetime of the τ lepton and of the weakly decaying c and b mesons, and I will discuss how the experimental data can be used to test the theoretical models. All measurements now available on the lifetime of the τ lepton and of the b quark come from e^+e^- -experiments^[1], while charmed mesons have been extensively studied also at fixed target machines. Since this meeting is focused on e^+e^- -physics, I will discuss only the e^+e^- -measurements and I will quote all available data when summarizing the results.

In the Standard Model of the weak interactions, the decay of leptons and quarks goes through the emission of a virtual gauge boson W^- which in turn decays into a lepton or quark pair. The lifetime of a heavy lepton l can be derived

by that of the μ assuming lepton universality :

$$\tau_l = \frac{192\pi^3}{G_F^2 m_l^5} \times BR(l \rightarrow e \nu_e \nu_l)$$

τ_l is expected to be shorter than τ_μ because the decay of a heavier lepton is favoured by having more phase space and more channels available, due to the higher mass. For a heavy quark Q the expression is the same, except for a factor which originates from quark "mixing" and that we will discuss in some detail later on.^[2]

The measurement of the τ lifetime is therefore a straightforward test of the $\tau - \mu$ universality. D's and F's lifetimes are important for understanding the decay mechanism of the charm quark; this should decay to s and to d with rates proportional to $\cos^2\theta_c$ and $\sin^2\theta_c$ respectively, θ_c being the Cabibbo angle. The b lifetime is of fundamental importance since it provides the first measure of the mixing of the b to the c quark (mixing angles are free parameters in the theory and must be determined experimentally).

The recent interest of most e^+e^- experiments in lifetime measurements is not surprising : τ physics is an exclusive of e^+e^- machines; heavy quark production is more abundant , and more easily separated from the background, in e^+e^- interactions. At the PEP/PETRA energy, the decay lengths of τ , D and B mesons are matched well enough to the spatial resolution of the drift chambers used for tracking.

In 1982 the τ lifetime was first measured by MARK II^[3] at the e^+e^- storage ring PEP; since then, most e^+e^- experiments have improved their ability to track particles near the interaction point (which is hidden in the vacuum chamber) and are pursuing a strong program of lifetime measurements of c and b hadrons. Very recently charm and τ lifetimes have been measured also at lower c.m. energy at CESR where the disadvantage of shorter decay paths is offset by higher cross sections and wider opening angles of the decay products.

1. EXPERIMENTAL METHOD AND DETECTORS

1.1 ANALYSIS TECHNIQUES

Ideally a lifetime measurement requires the identification of the production vertex, the decay vertex and the decay products; the lifetime τ is calculated from the path length L (distance between the two vertices), the mass and the momentum of the decaying particle:

$$L = \gamma\beta c\tau$$

Optical devices, like bubble chambers and emulsions, are very suitable for lifetime experiments since they provide excellent spatial resolution and the identification of both the production and the decay vertices in the active medium. For many years lifetimes have been measured using these techniques at fixed target machines; the main disadvantages were low statistics and systematic biases due to the fact that the detection efficiency varies with the flight path.

In e^+e^- experiments the production point is inside the vacuum pipe and the primary vertex must be evaluated by extrapolating measured tracks for several centimeters. The τ lepton can not be fully reconstructed because of the presence of a neutrino in the decay products and also b mesons can not be completely identified in the detectors at PEP or PETRA. A different analysis method is often used, the so called "impact parameter", *i.e.* the distance of closest approach of a track to the origin. This is calculated for single tracks, thus does not require full reconstruction of the decaying particle. The method relies on the fact that a finite lifetime shifts the mean of the impact parameter distribution toward positive values. A Montecarlo is then needed to determine the relation between lifetime and average impact parameter.

Most detectors at PEP and PETRA are "general purpose"; they consist of a tracking device in a magnetic field to measure direction and momentum of the charged tracks, and some particle identification techniques for hadrons and/or leptons and photons. A lifetime measurement requires the selection of the events,

and the measure of the flight path or the impact parameter. In the first stage, the analysis makes use of practically all of the detector's features, and in the last step the quality of the tracking system is critical. MARK II pioneered the use of a "vertex detector" *i.e.* a high precision small drift chamber around the vacuum pipe; several detectors have now installed such devices; the one built by MAC is the closest to the beams.

1.2 THE DETECTORS

Lifetime measurements in e^+e^- annihilations have been performed by MARK II, MAC, HRS and DELCO at PEP, at E_{cm} of 29 GeV ; by TASSO and JADE at PETRA, at E_{cm} 35 - 42 GeV and by CLEO at CESR at 11 GeV . I will briefly describe the detectors' features which are more relevant in the lifetime analysis, referring to the literature for more details.

MARK II is a general purpose detector.^[4] The tracking device is a drift chamber with 16 cylindrical layers, at radii between 41 and 145 cm, in a 4.6 KG axial magnetic field. Outside the magnet core a lead-liquid argon calorimeter is used for detection and energy measurement of neutral particles. Four walls of steel interspaced with proportional tubes are placed above, below and to either side of the detector to provide muon identification over $\approx 45\%$ of 4π . In 1981 the vertex detection was improved by inserting a small cylindrical high precision drift chamber around the beam pipe, with 4 layers at radii $\approx 11cm$ and 3 layers at $\approx 30cm$. The point resolution in hadronic events is 100μ .

MAC^[6] combines precision tracking with calorimetric measurements over practically the total solid angle. Charged particles are tracked in a vertex detector and in a central drift chamber, immersed in a solenoidal magnetic field of 5.7 KG. Muon identification is very clean and is available over 97% of the solid angle. Muon momentum is measured twice : once in the inner drift chamber and once in the outer ones, using the deflection in the toroidal field of the magnetized iron absorber. Electrons are identified by combining the information from central

tracking and the electromagnetic calorimeter. The MAC vertex chamber will be described in more detail in next section.

HRS (High Resolution Spectrometer)^[6] is a detector with a powerful superconducting solenoidal magnet whose large volume is filled with a system of three tracking devices: a vertex chamber, consisting of four layers of drift *straw* tubes, a central 15 layers chamber and an outer drift chamber with two layers of tubes located 1.9 m from the beam axis. The high value of the magnetic field, 1.6 Tesla, and the length of the tracks, almost 2m, are the main characteristics of this detector, and provide an excellent momentum resolution, 0.1% at 1 GeV/c, and a precise extrapolation of tracks to the interaction point.

DELCO is an open geometry magnetic detector^[7] with segmented Čerenkov counters and accurate charged particle tracking in a drift chamber. Electrons can be identified over 52% of the solid angle by combining information from the tracking, the Čerenkov and the shower chamber. Hadron misidentification is kept at the 0.1% level.

The TASSO detector^[8] has a large drift chamber immersed in a solenoidal field, which provides precise particle tracking; for lifetime purposes a vertex drift chamber has been recently added. Two thirds of the azimuth are covered by electromagnetic calorimeters, the remainder by Čerenkov and shower counters.

JADE is also a general purpose apparatus^[9] : charged tracks are measured in a cylindrical jet chamber; up to 48 points are measured per track, with an accuracy of about 170μ . Electrons are identified by the measurement of the momentum and the energy loss dE/dx in the jet chamber, and by the electromagnetic shower energy deposited in a lead glass counter array. Muons are identified as penetrating charged particles in a system of hadron absorbers and drift chambers.

CLEO^[10] operates at the CESR storage ring at Cornell and is a large solid angle magnetic detector. Tracking is performed in a 10-layer vertex detector and in a central drift chamber with 17 cylindrical layers which also provides dE/dx

measurements. This system operates inside a 1 T magnetic field produced by a superconducting coil. Charged hadron identification is achieved by time of flight counters and by dE/dx , measured in a set of proportional wire chambers, in addition to the central drift. A lead-proportional tubes electromagnetic calorimeter, an iron absorber and external muon chambers complete this apparatus.

1.3 THE MAC VERTEX DETECTOR

This high precision drift chamber^[11] was installed in October 1984. It consists of 6 cylindrical layers at radii from 4.6 to 8.4 cm, with a total of 324 drift tubes contained in a pressurized vessel. The tubes are *straws* made of aluminized mylar, 432 mm long and 6.9 mm in diameter; they are arranged in 3 double-layers. The first layer in each of the 3 pairs are tightly packed, with no more than 25μ between them; the centers of the second layer are offset by a straw radius, so that the dead space in one layer is covered by the wire in the other, as shown in Fig. 1 .

To install this chamber inside the MAC central drift (inner radius 11 cm), a new beam pipe and masking system had to be designed. The beryllium vacuum pipe used is very thin (0.6% of a radiation length) and serves also as the inner gas seal for the chamber, to minimize multiple Coulomb scattering. Its radius is 3.4 cm, the smallest ever in a e^+e^- machine. The gas used was a mixture of 50% Argon , 49% CO_2 and 1% CH_4 and was pressurized to 4 Atm. No other device has ever been operated in a e^+e^- machine so close to the beam, still the chamber performance has been very satisfactory and the operation very clean, thanks to the shielding structure. The average number of extra hits due to background was only two per beam crossing. The measured point resolution, averaged over the straw radius (it deteriorates near the wire), was 50μ for Bhabha events. The error in extrapolating a track to the production point was measured from the "miss distance" Bhabha events and was found to be 90μ , a factor 4 improvement respect to the tracking with only the MAC central drift. VC tracks for a typical event are shown in fig. 2 .

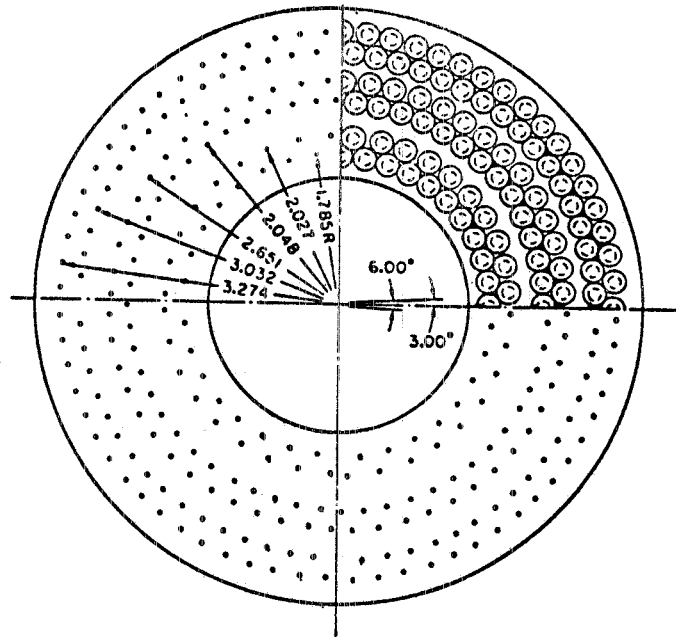


Fig 1. Layout of the vertex chamber end-plate, showing the arrangement of the 6 layers of tubes.

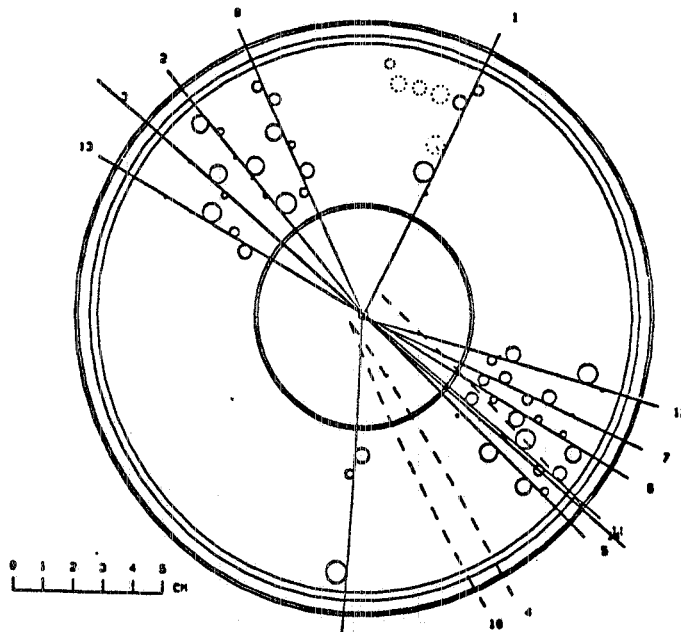


Fig 2. Hits in the Vertex chamber from a multihadron event. The hits are represented by circles which radius is proportional to the measured drift time, and tracks are fitted to be tangent to these circles. Dashed lines indicate extra tracks in the central drift

2. τ LIFETIME

2.1 THE THEORY

The τ lifetime can be calculated using very simple, basic assumptions: if the τ behaves like the μ , *i.e.* the charged weak current responsible for the τ decay has the *universal* Fermi strength and $V - A$ structure, and if the ν_τ is massless, then comparing the diagrams fig. 3

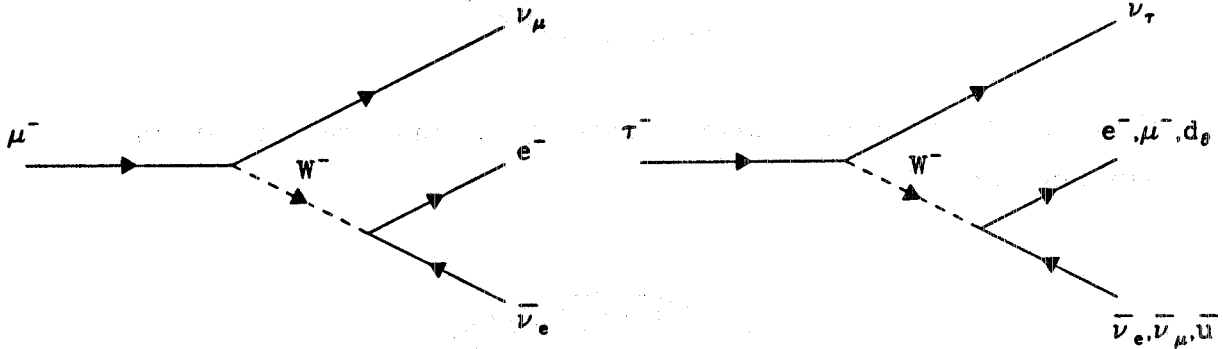


Fig 3: weak decay of the μ and the τ leptons

we have:

$$\tau_\tau = \tau_\mu \times \left[\frac{m_\mu}{m_\tau} \right]^5 \times BR(\tau \rightarrow e \bar{\nu}_e \nu_\tau)$$

using for the branching ratio the value^[12]

$$BR(\tau \rightarrow e \bar{\nu}_e \nu_\tau) = (17.9 \pm 0.4)\%$$

we get:

$$\tau_\tau^0 = (2.86 \pm 0.06) \times 10^{-13} \text{sec}$$

where the uncertainty is mainly due to the error in the measurement of the branching ratio. The τ 's are pair produced in e^+e^- annihilation, so they have the same energy as the beam: the expected lifetime translates into a flight path of $\approx 700\mu$ at PEP and of $\approx 1\text{mm}$ at PETRA's highest E_{cm} .

The measurement of the τ lifetime is therefore a test of the simple hypothesis we have used for calculating τ_τ^0 : any deviation would have important consequences on the theory. A longer lifetime could indicate that the ν_τ is not massless; Fig. 4 shows the dependence of τ_τ from m_{ν_τ} ;

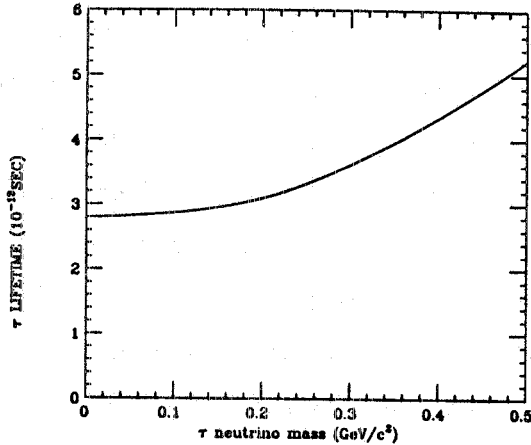


Fig 4: Dependence of τ_τ^0 from the ν_τ mass

the lowest limit on the ν_τ mass has been obtained by the Argus experiment^[13] studying the decay $\tau \rightarrow 3\pi\nu_\tau$, and is $< 70\text{MeV}$ at 95 % c.l. and this makes the lifetime measurement a quite stringent test.

2.2 THE EXPERIMENTS

In e^+e^- annihilation τ 's are produced in pairs:

$$e^+e^- \rightarrow \tau^+\tau^-$$

τ decays channels are:

$\tau \rightarrow e\bar{\nu}_e\nu_\tau$	17.9 ± 0.4	%
$\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau$	17.5 ± 0.3	%
$\tau \rightarrow 1h + \text{neutrals}$	51.4 ± 0.6	%
$\tau \rightarrow 3h + \text{neutrals}$	13.1 ± 0.3	%

the experimental signature for these events is quite clear: they appear in the detectors as two almost back to back jets, with low multiplicity, low mass, high

energy. Typical configurations are 1 - 1 , 1 -3 , and 3 - 3 charged prongs, which can be easily separated from hadronic events, which have higher multiplicity, and from two photons events , because of energy and sphericity

Several experiments have measured τ lifetime at PEP, PETRA and CESR ; basically two methods are used: the flight path and the impact parameter. The first consists in the measurement of the distance between the interaction point and the 3-prongs vertex; thus only events with topology 1-3 and 3-3 prongs can be used. The average distance is predicted to be 700μ and 1000μ respectively at PEP and at PETRA. In the impact parameter method, the closest distance of approach of all tracks is measured respect to the interaction point. The average value is much smaller than the decay length, $\approx 40\mu$ at PEP; this disadvantage is offset by the larger statistics which makes possible a precise determination of the position of the mean , even if the shift from zero is small.

Because of the high statistics available and the better control of the systematic effects, τ lifetime measurements are often used as calibrations for the b-lifetime. In the following, I will discuss in some detail one example for each of the two analysis methods: a precise measurement by the MARK II collaboration^[14] which was performed using the flight path method and a recent MAC analysis^[15] which uses the impact parameter technique and a data sample of more than 12,000 events τ events.

2.3 MARK II MEASUREMENT

The selected events are required to have a 1-3 or 3-3 charged prongs topology, with 3 tracks in one emisphere, and zero total charge. The total energy must be over 5 GeV , to reject two-photon events, and below 26 GeV , to avoid contamination from radiative Bhabha's. The invariant mass of the 3 prongs must be between 0.7 and $1.5 \text{ GeV} / c^2$, and the energy between 3 and 15 GeV . "Quality" cuts are then applied to the tracks to ensure that only well measured tracks are used in the lifetime analysis. The background is estimated by Montecarlo to

be 7% , 4% of which from low multiplicity multihadronic events and 3% from 2-photons reactions. Fig. 5 shows a typical 1 - 3 prongs event from MARK II, with a blow up of the interaction area.

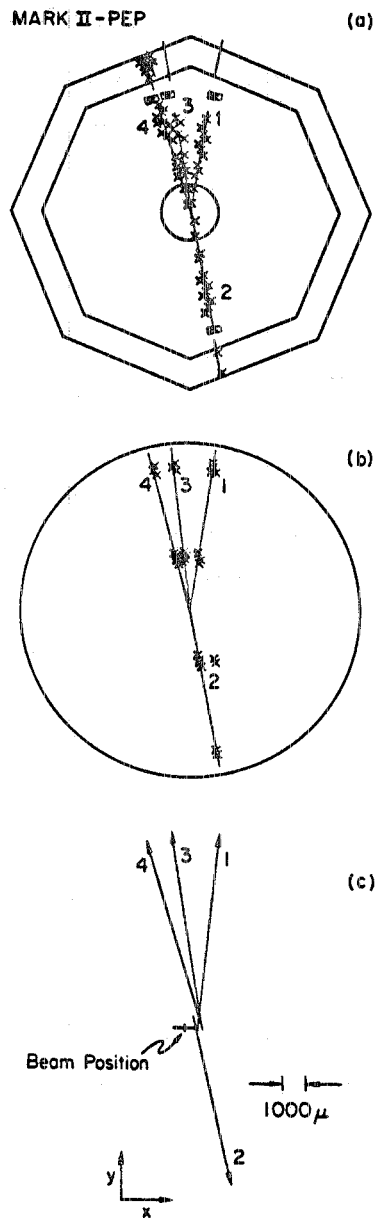


Fig 5: Typical τ event in MARKII
a) general view, b) as seen in the VC, c) blow up of the vertex region

The decay length is calculated from the beam position, the 3-prong vertex position and the τ direction, assumed to be the same as the momentum of the 3 tracks system. What is measured is the projection in the xy plane (fig. 6), where the resolution is more than an order of magnitude better than along the beam direction. The r.m.s. beam size is $\approx 500\mu$ horizontally and $\approx 50\mu$ vertically. Its center is well known and stable: its position is continuously monitored on a run by run basis using Bhabha events. The decay vertex is determined , with its error ellipse, from the three trajectories and a χ^2 cut is applied, to select only well measured vertices.

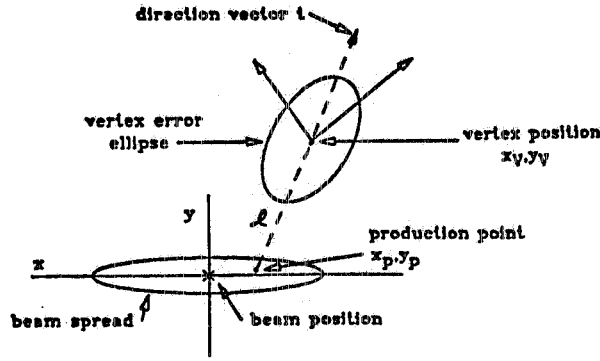


Fig 6: Estimation of the decay path

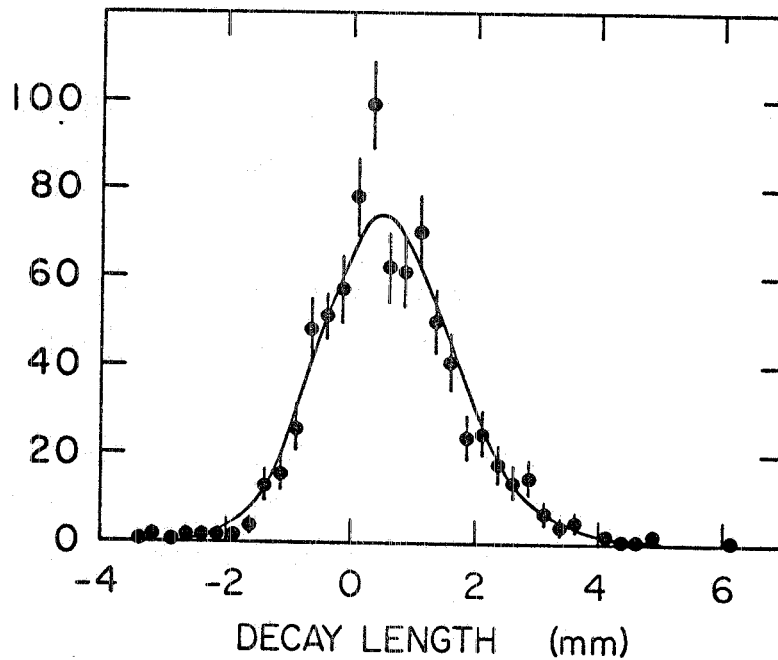
The best estimate for the projected decay length is given^[16] by:

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

where (x_v, y_v) is the vertex position , t_x and t_y are the τ direction cosines, σ_{ij} is the sum of both the beam position and the vertex error matrices. The polar angle θ is then used to obtain the three-dimensional decay length

$$l = \frac{l_{xy}}{\sin(\theta)}$$

the error on l depends on the opening angles and the orientation of the decay, the average $\sigma(l)$ is $\approx 1000\mu$; events with $\sigma(l) > 1.4$ mm are discarded. The decay length distribution obtained after all the cuts is shown in Fig. 7 ; the mean is obviously positive and its shape is asymmetric.



*Fig 7: Decay length distribution for τ events (MARK II)
the solid curve represents the fit to the data*

A fit is then performed , with a maximum likelihood technique which takes the decay length error into account, for each event. The fitting function is the convolution of the gaussian error and an exponential decay distribution. The result of the fit is an average decay length of $\langle l \rangle = 635 \pm 36\mu$; the lifetime is calculated using for E_τ the value 13.9 GeV , lower than E_{beam} because of the radiative corrections :

$$\tau_\tau = (2.86 \pm 0.16) \times 10^{-13} \text{sec}$$

where 0.16 is the statistical error.

A number of effects have to be considered in order to evaluate the systematic error; MARK II has studied a *control sample* of events which are not $\tau^+\tau^-$, but have three tracks with similar characteristics; the path length distribution's mean of the control sample is found to be slightly positive:

$$\langle l^{control} \rangle = 79 \pm 23\mu$$

The same effect is found in a sample selected with the same criteria in the Mon-

tecarlo; in this case it is possible to detect the source of the offset of the average: it is due to the finite lifetime of the charm and beauty hadrons present in the sample.

The contribution to the mean of the background is calculated to be $31 \pm 22 \mu$, where the error is the statistical error from the Montecarlo. Other effects include multiple scattering ($< 30 \mu$), shifts in the beam position ($< 15 \mu$), track *quality* cut ($< 20 \mu$), cut in the decay length error ($< 25 \mu$). To account for unknown biases, an extra error of $\pm 15 \mu$ was added to the previous one; summing all these errors (in quadrature), MARK II quotes a systematic error of 57μ and a lifetime:

$$\tau_{\tau} = (2.86 \pm 0.16 \pm 0.25) \times 10^{-13} \text{sec}$$

2.4 MAC MEASUREMENT

The MAC selection of τ events is similar in principle to the one previously described; the cuts are applied on calorimetric quantities measured by this detector: the total calorimetric energy is required to be between 6 and 25 GeV, the sphericity of the event to be less than 0.035, and all calorimeter hit clusters with an energy greater than 1 GeV to be within 30° of the sphericity axis. The invariant mass must be less than 3 (4) GeV in the hemisphere with the smaller (larger) mass; the scalar sum of the charged track momenta is required to be at least 4 GeV /c. For the lifetime measurement the impact parameter technique is used: for each track the distance of closest approach δ to the interaction point is found, in the plane transverse to the beam direction. The expected average of δ , due to the τ lifetime is $\approx 40 \mu$, *i.e.* much smaller than the resolution in δ ; it follows that δ can be negative nearly as often as positive. The sign of δ is chosen positive (negative) when the decay appear to be forward (backward). Fig. 8 shows the distribution of δ weighted by $1/\sigma_{\delta}^2$. Tracks with $\sigma_{\delta} > 1 \text{mm}$ are rejected; approximately 90% of all tracks have σ_{δ} between 0.5 and 1 mm. The final sample contains 23,584 tracks and has a median $\langle \delta \rangle = 43.6 \pm 5.0 \mu$; The median rather than the mean is used in order to reduce sensitivity to background and K decays;

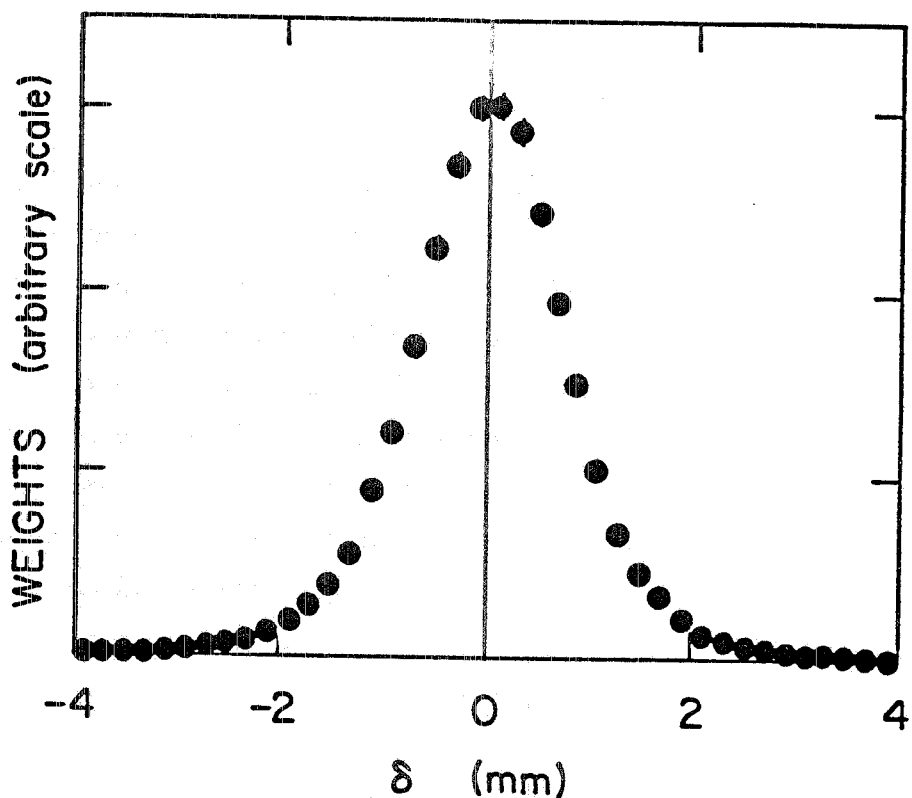


Fig 8: Impact parameter distribution for τ events (MAC)

the median is expected to be nearly equal to the mean for an exponential decay distribution with decay constant much smaller than the experimental resolution.

The median is related to the lifetime by a constant α which is found by Montecarlo; the background present in the sample is estimated to be 3.9%. MAC result is

$$\tau_\tau = (3.15 \pm 0.36 \pm 0.4) \times 10^{-13} \text{ sec}$$

where the first error is statistical, and the second is systematic. The latter is dominated by the uncertainty in α and by possible biases in δ which have been carefully investigated. The analysis of a large sample of Montecarlo events with τ lifetime set equal to zero gives $\langle \delta \rangle = 3.92 \pm 2.2\mu$; other possible systematic biases which could not be simulated in the Montecarlo have been studied using tracks in hadronic events.

2.5 SUMMARY OF τ LIFETIME

Several detectors have measured the τ lifetime using the path length and/or the impact parameter methods. Recently MAC has performed a more precise measurement using data collected with its new vertex chamber. The distribution of all available results is consistent with statistical fluctuations expected from the statistical error given by each measurement. The values are reported in Table I and plotted in Fig. 9. The "world average" is the weighted mean (statistical errors only are used); the early measurements have not been included. '86 results are unpublished and should be considered preliminary. The two MAC measurements refer to different data samples and are therefore independent.

TABLE I

τ Lifetime Measurements

Experiment	Method	V.C.	# Decays	τ Lifetime ($10^{-13}sec$)
MARK II '82	Decay Path	No	126	4.6 ± 1.9
MAC '82	Decay Path	No	280	$4.1 \pm 1.2 \pm 1.1$
CELLO '82 ^[17]	Decay path	No	78	$4.7^{+3.9}_{-2.9}$
JADE '84 ^[18]	Impact Par.	No		3.5 ± 1.1
DELCO '84 ^[19]	Impact Par.	No		2.9 ± 0.8
MARK II '84	Decay Path	Yes	805	$2.86 \pm .16 \pm .25$
HRS '85 ^[20]	Decay Path	Yes	134	$2.8 \pm 0.4 \pm 0.5$
TASSO '85 ^[21]	Decay Path	Yes	48	$3.18^{+0.59}_{-0.75} \pm .56$
MAC '85	Impact Par.	No		$3.15 \pm 0.36 \pm 0.40$
CLEO '86 ^[22]	Decay Path	Yes	5867	$2.92 \pm 0.23 \pm 0.30$
MAC '86 ^[23]	Impact Par.	Yes		2.84 ± 0.16
Average '84-'86				2.89 ± 0.10

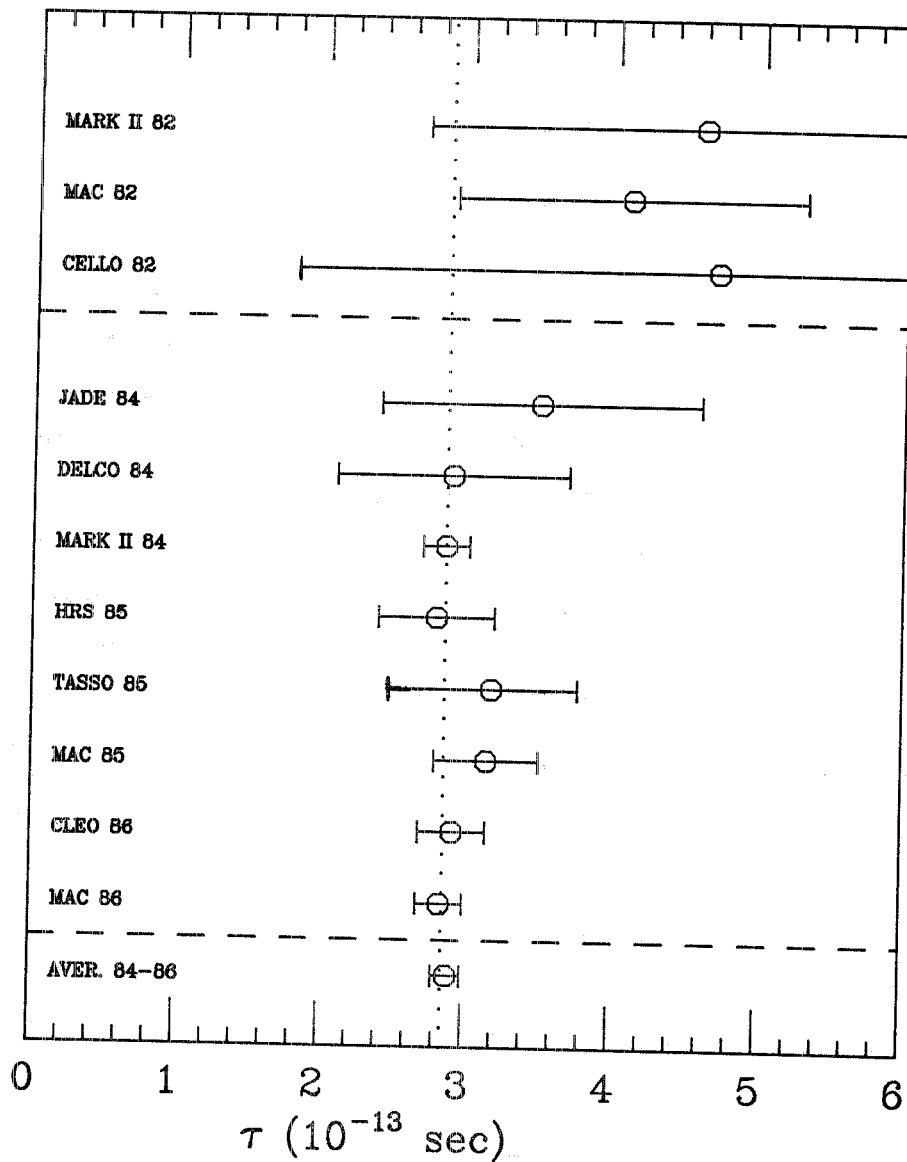


Fig 9: τ_τ measurements; the dotted line represents τ_τ^0

The measurements agree well between each other and with the theory. The $\mu - \tau$ universality is verified at the few % level ; this is an important result, but is still quite far from the precision at which $e - \mu$ universality has been verified. In order to improve the sensitivity of this test , one should also reduce the uncertainty in the theoretical value τ_τ^0 , which comes essentially from the error in the branching fraction $\tau \rightarrow e\bar{\nu}_e\nu_\tau$.

3. CHARM LIFETIMES

3.1 THEORETICAL MOTIVATION

The decay of a charmed meson is described, in the simplest approach, as the decay of a free c quark into a W boson and into a strange quark s (or a d quark, in Cabibbo suppressed modes), while the lighter quark merely acts as a spectator (Spectator Model). It follows that D^0 , D^+ , F^+ should all have the same lifetime and the semieleptonic branching ratios should be 20%, since there are 5 channels open to the W 's decay. It was noted^[24], that QCD corrections to the weak Hamiltonian provide a small non-leptonic enhancement. Many authors have calculated this effect and the estimates for the semieleptonic branching ratio range from 13% to 19%, roughly the same for D^0 and D^+ .

The first clue that the D^0 and the D^+ lifetimes could be considerably different came in 1978 from the measurements at SPEAR of the semileptonic branching ratios. B_{sl}^0 and B_{sl}^+ .

These are related to the lifetimes :

$$B_{sl}^0 = \frac{\Gamma_{sl}(D^0)}{\Gamma_{Tot}(D^0)} = \Gamma_{sl}(D^0)\tau_{D^0}$$

$$B_{sl}^+ = \frac{\Gamma_{sl}(D^+)}{\Gamma_{Tot}(D^+)} = \Gamma_{sl}(D^+)\tau_{D^+}$$

and since the semileptonic widths of D^0 and D^+ are equal (at least up to Cabibbo suppression), the ratio of the branching ratios is the same as the ratio of the lifetimes. MARK II^[25] and DELCO^[26] found the surprising result that B_{sl}^+ is significantly bigger than B_{sl}^0 .

In the following years there has been a flurry of experiments at CERN, FER-MILAB and SLAC to measure D^0 and D^+ lifetimes using optical techniques; more recently PEP and PETRA detectors, upgraded with vertex chambers, have reached enough sensitivity to become competitive. CLEO has now preliminary

results at lower energy, where cross sections are higher and charm events are easier to identify. Several experiments at fixed target machines are now using a new technique, the so called *silicon strips* detectors, which combine the high resolution of the optical devices and the advantages of the electronic experiments.

3.2 D^0 LIFETIME: THE METHOD

Charm production is copious in e^+e^- annihilation at E_{cm} at or above the ψ'' : almost one half of all multihadronic events contain a pair of charmed particles. Unfortunately lifetime measurements have to be performed at E_{cm} far enough from the threshold, where only a small fraction of the events can be *tagged* as coming from a primary pair of c quarks and only a handful of D or F mesons can be identified in an exclusive channel *i.e.* fully reconstructed. The low multiplicity, all charged tracks decay modes, which are the easiest to reconstruct, have very small branching ratios, of the order of few %. More abundant channels have higher multiplicity and generally have one or more π^0 's, experimental efficiencies are then very small and the combinatorial background very high. D^0 channels which have been used for lifetime measurements are:

$$\begin{aligned}
 D^0 &\rightarrow K^- \pi^+ && (4.9 \pm 0.9 \quad \%) \\
 D^0 &\rightarrow K^- \pi^+ \pi^0 && (20.4 \pm 4.1 \quad \%) \\
 D^0 &\rightarrow K^- \pi^+ \pi^- \pi^+ && (11.8 \pm 2.3 \quad \%)
 \end{aligned}$$

To reduce the combinatorial background, all experiments use D^0 's from the decay $D^{*+} \rightarrow D^0 \pi^+$, in order to take advantage of the peculiar kinematics of this reaction. Since the mass difference between the D^{*+} and the D^0 is very close to the π^+ mass, the Q of the reaction is few Mev. This drastically limits the phase space, thus suppressing the combinatorial background. To further improve the signal to background ratio all experiments use a cut in z , the ratio E_{D^0}/E_{beam} ; the studies on the c fragmentation function have proved that most charmed events have high z . The cut in z has an added bonus for the lifetime measurement: it practically eliminates the contribution of the D^0 's from the B decays, which have a softer momentum distribution.

The steps that most experiments use in the analysis are the following: first all multihadronic events produced in the one photon e^+e^- annihilation are selected. For each event the invariant mass of any oppositely charged pair of tracks is calculated, in the two mass assignments $\pi - k$, or $k - \pi$. Pairs with $M_{k\pi}$ or $M_{\pi k}$ in the D^0 mass region are selected and combined with the remaining tracks in order to make $(K^-\pi^+)\pi^+$ or $(K^+\pi^-)\pi^-$ combinations. The z cut is then applied and the mass difference $M_{(K\pi)\pi} - M_{K\pi}$ plotted. The $D^{*+} \rightarrow D^0\pi^+$ events appear as a narrow peak centered at $\Delta_M = 145 \text{ Mev}$; fig. 10 shows for example the HRS distribution, which has the narrowest peak, thanks to the superior momentum resolution. Other D^0 decay channels that have been used in a similar fashion are $K\pi\pi^0$ and $K\pi\pi\pi$

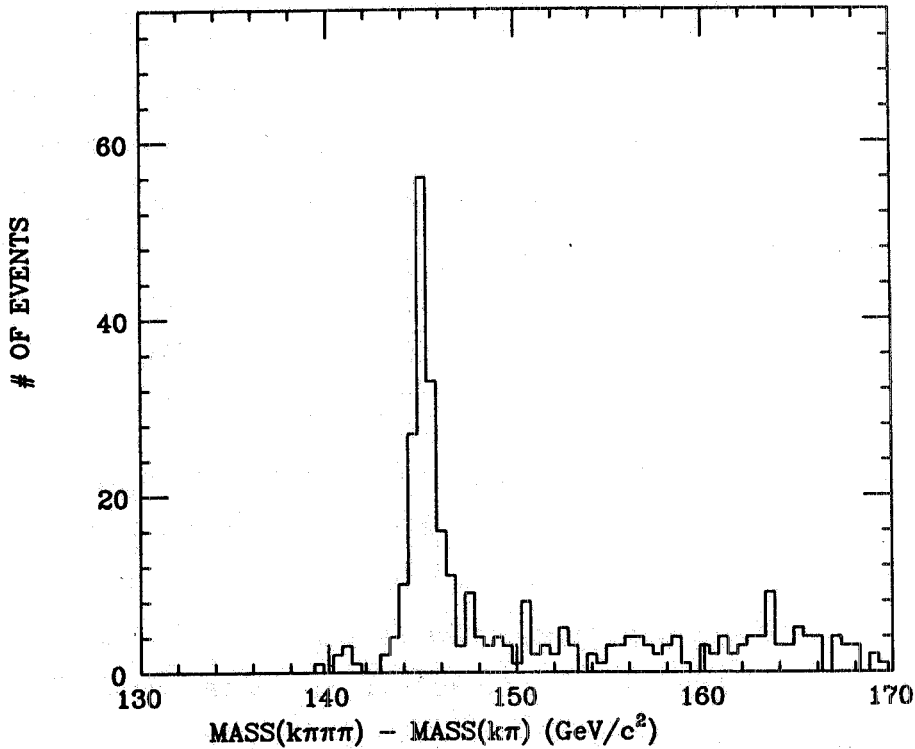


Fig 10: $D^{*+} - D^0$ Mass difference, $z > 0.4$ (HRS)

Once D^0 's are selected, "quality" cuts are applied to the tracks from the

D^0 's decays and to the χ^2 of the vertex, and the decay path is calculated with its error, using the same technique described for the τ analysis. What is actually measured is the projected decay path l_{xy} which is then corrected using the polar angle θ to find the actual decay length. This is, in turn, converted into the proper decay time using the measured D^0 momentum:

$$t = \frac{l}{\beta\gamma c}$$

a maximum likelihood fit is performed to obtain the lifetime; Montecarlo studies and checks on the data are used to evaluate the systematic effects that could bias the result. A control sample can be obtained by substituting for the D^0 the track combinations with $M_{k\pi}$ in the side bands.

3.3 D^0 LIFETIME: THE RESULTS

Five e^+e^- experiments have measured, up to now, the D^0 lifetime; I will describe the main characteristics of each one's analysis, and give the results.

MARK II. The final data sample^[27] consists of 74 events, with a $D^{*+} - D^0$ mass difference between 143 and 149 Mev; 39 in the $D^0 \rightarrow K^-\pi^+$ channel, and 35 in the $D^0 \rightarrow K^-\pi^+\pi^0$ mode (see Fig. 11). The background is estimated to be 4.6 events. The contribution from B decays is suppressed by the cut $z > 0.6$ and is evaluated at $(3 \pm 2)\%$. Fig. 12 shows the lifetime's distribution for the 74 D^0 events and for the control sample. The most probable mean decay time for the D^0 is found by a maximum likelihood fit of the 74 measurements to an exponential distribution convoluted, event by event, with the error; the fit includes effects due to the background and to B feed-down; the resulting lifetime is:

$$\tau_{D^0} = (4.7_{-0.8}^{+0.9} \pm 0.5) \times 10^{-13} \text{s}$$

The control sample consists of events having a fake D^0 , *i.e.* tracks not satisfying D^0 requirements, but having roughly the same kinematics; the mean decay time of these false D^0 's was measured to be $(0.4 \pm 0.2) \times 10^{-13}$ s.

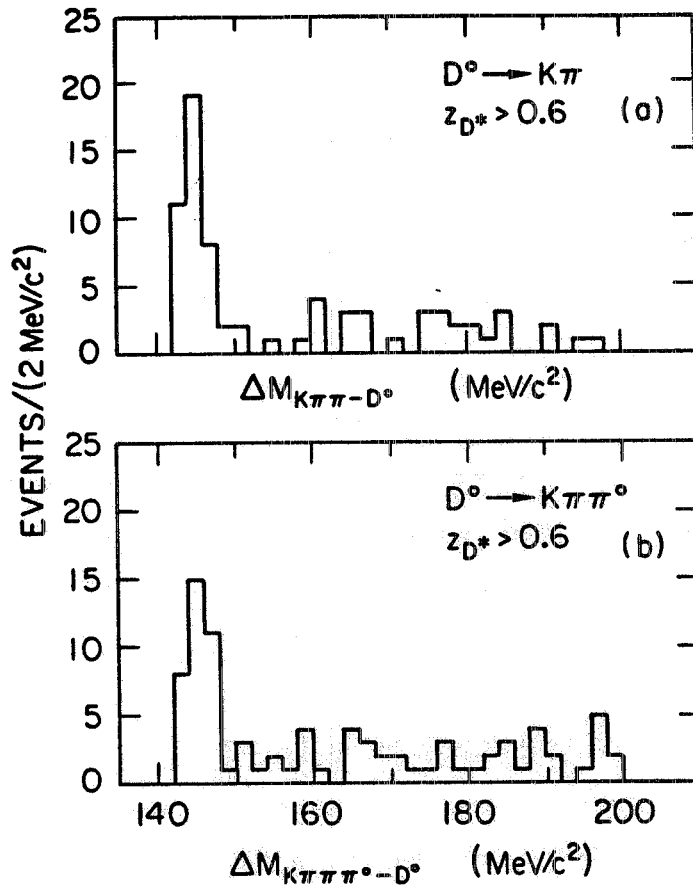


Fig 11. $D^{*+} - D^0$ Mass difference (MARK II)

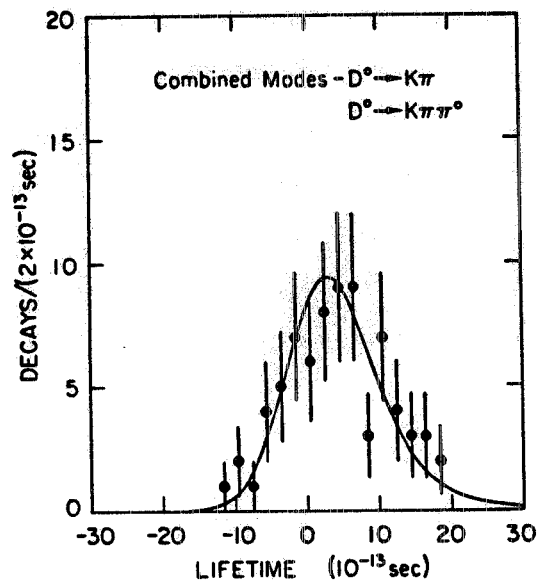


Fig 12. D^0 lifetime distribution (MARK II)

DELCO.^[28] The method used is the impact parameter: D^{*+} decays in $D^0\pi$ or in $D^0\pi(X)$ are selected; X, which is not observed, is typically a π^0 . Kaons are identified by using the Cerenkov information; the D^0 candidates are the $K\pi$ pair with invariant mass between 1.45 and 2.2 GeV/c^2 ; the signal region is taken to be $\Delta M < 0.1625\text{GeV}/c^2$. The impact parameter of both the kaon and the pion are measured in the xy plane, with respect to the beam center measured by the beam position monitor. After all analysis cuts, 269 tracks are left for the measurement: the result of a maximum likelihood fit to the impact parameter distribution (see Fig. 13) is $151.7 \pm 42.3\mu\text{m}$. This method is found to be insensitive to the choice of specific cuts and uncertainties in backgrounds and gives for the D^0 lifetime:

$$\tau_{D^0} = (4.6 \pm 1.5^{+0.6}_{-0.5}) \times 10^{-13} \text{ s}$$

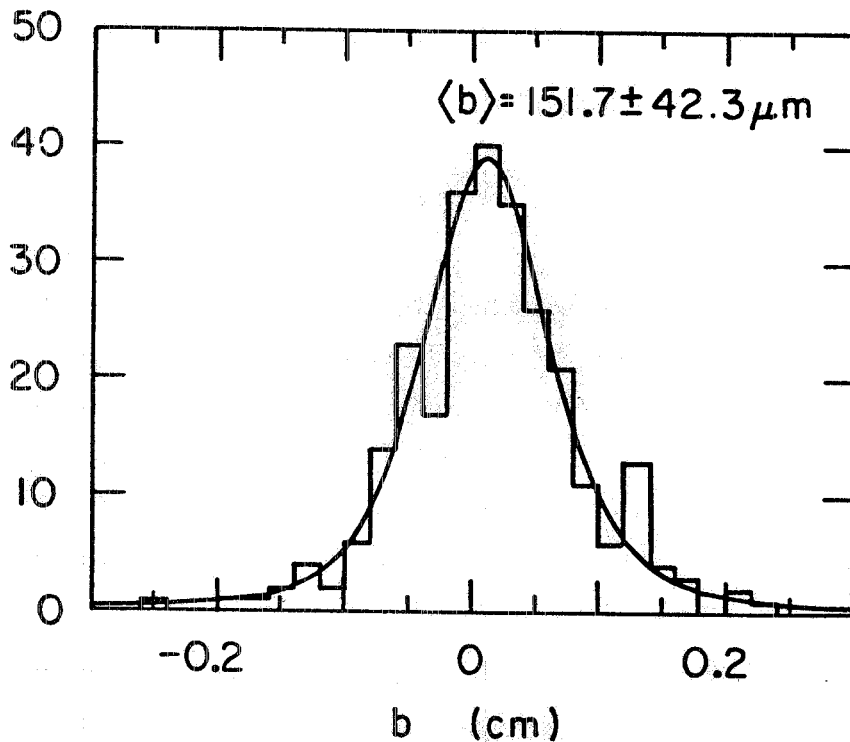


Fig 13. Impact parameter distribution (DELCO)

HRS. The excellent mass resolution available to this apparatus provides a clean sample of D^0 's events, even with lower z cut; D^0 's are selected in the $K\pi$ channel with a technique similar to that of MARK II, but a cut of $z=0.4$ is applied to the D^{*+} 's; B 's feed-down is checked using events with z between 0.2 and 0.4 , instead than by Montecarlo, as done by the other experiments. The *straw* vertex chamber is used to determine the decay path of the 53 D^0 events which pass all analysis cuts; the preliminary result^[29] is:

$$\tau_{D^0} = (4.2 \pm 0.9 \pm 0.6) \times 10^{-13} \text{ s}$$

TASSO.^[30] The event selection criteria are similar , but the vertex reconstruction method is slightly modified. D^0 's are required to have good three dimensional vertex fit, instead of two-dimensional. The vertex determination precision is further improved by the constraint of $M_{K\pi}$ to the D^0 mass. The final sample consists of 8 D^0 's, 6 in the $K\pi$ channel, 2 in the $K\pi\rho$ decay mode. B feed-down is estimated to be less than 5%, thanks to the $z > 0.6$ cut; the preliminary result is:

$$\tau_{D^0} = (4.6^{+2.9+1.0}_{-1.7-0.3}) \times 10^{-13} \text{ s}$$

CLEO. This detector has been recently upgraded with a vertex chamber; it runs at lower energy, where D^0 's cross sections are higher and D^0 's from B decays can be eliminated by running below the B production threshold. The analysis is similar to that of MARK II and HRS and is based on the identification of the D^{*+} decay chain, and the measure of the D^0 decay path. In order to reduce the combinatorial background the D^0 candidates are required to have momentum greater than 2.5 GeV/c.

A preliminary result^[31] is based on a sample of 313 events , a very high statistics , compared with the PEP/Petra experiments; the background is estimated to be 24 events. Fig. 14 shows the decay length distribution; the error-weighted mean is $(132 \pm 27)\mu m$, and the calculated lifetime:

$$\tau_{D^0} = (4.6 \pm 0.9 \pm 0.7) \times 10^{-13} \text{ s}$$

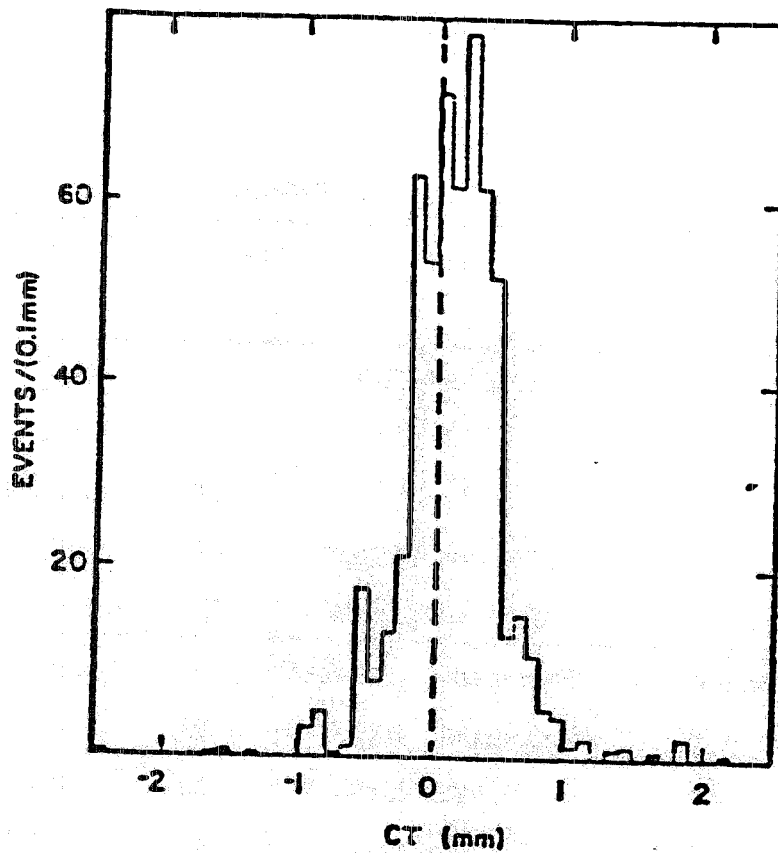


Fig 14. Decay path distribution for D^0 events (CLEO)

These results, together with the ones obtained in fixed target experiments,^[32] are summarized in Table II and plotted in Fig. 15. All measurements, although performed with different techniques, are consistent within the statistical errors indicated. After the confusion of the first results, widely scattered, the situation is now quite satisfactory; the "world average", i.e. the weighted mean of the available measurements (statistical errors only are included) that we obtain from Table II is:

$$\langle \tau_{D^0} \rangle = (4.32 \pm 0.18) \times 10^{-13} \text{ s}$$

TABLE II

D^0 Lifetime measurements

Experiment	Technique	Beam	#decays	D^0 Lifetime (10^{-13} sec)
MARKII	Drift Ch.	e^+e^- 29 GeV	74	$4.7^{+0.9}_{-0.8} \pm 0.5$
DELCO	"	" "		$4.6 \pm 1.5^{+0.6}_{-0.5}$
HRS	"	" "	53	$4.2 \pm 0.9 \pm 0.6$
TASSO	"	$e^+e^- \approx 40$ GeV	10	$4.6^{+2.9+1.0}_{-1.7-0.3}$
CLEO	"	$e^+e^- \approx 11$ GeV	313	$4.6 \pm 0.9 \pm 0.7$
SHF	Bubble Ch.	Photoprod. , 20 GeV	50	$6.1 \pm 0.9 \pm 0.3$
Na-16	"	Hadroprod. 360 GeV	16	$4.1^{+1.3}_{-1.0}$
Na-27	"	" 400 GeV	129	$4.2^{+0.5}_{-0.4}$
Na-18	"	" 340 GeV	9	$4.1^{+1.6}_{-0.9}$
E-531	Emulsion	ν Interaction	58	$4.3^{+0.7+0.1}_{-0.5-0.2}$
WA-58	"	Photoprod. 100 GeV	44	$3.6^{+1.2}_{-0.8} \pm 0.7$
Na-1	Si strips	" "	51	$4.3^{+1.9}_{-0.9}$
Na-11	"	Hadroprod. 200 GeV	26	$3.7^{+1.0}_{-0.7} \pm 0.5$
ACCMOR	"	" "	42	$3.9^{+0.6}_{-0.5}$
E-691	"	Photoprod. 200 GeV	672	$4.4 \pm 0.3 \pm 0.2$

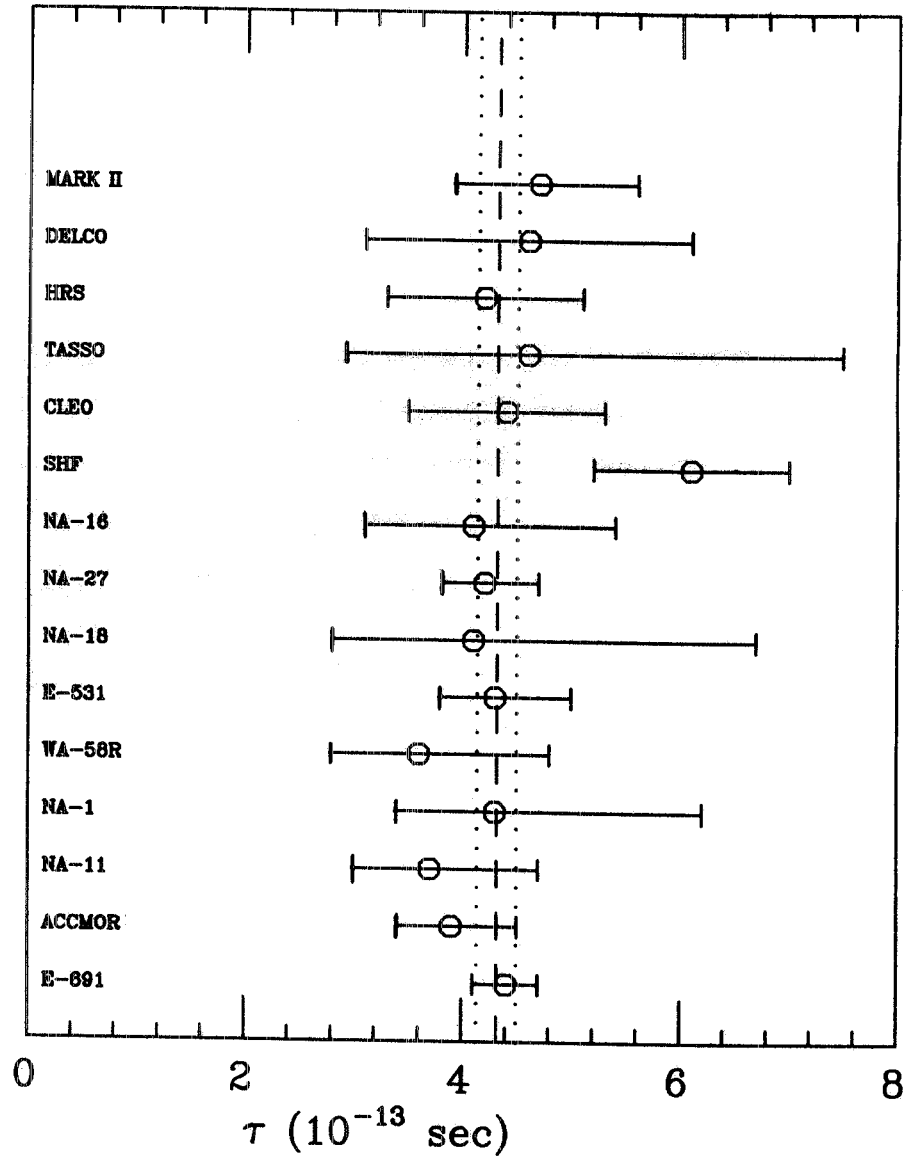


Fig 15: D^0 Summary of D^0 lifetime measurements. The dashed line represents the world average, the dotted lines are the $\pm 1\sigma$ band delimiters.

3.4 D^+ LIFETIME

Three e^+e^- experiments, MARK II, HRS and CLEO have measured both the D^0 and the D^+ lifetimes; The D^+ lifetime can be measured using an analysis technique similar to the one previously described for the D^0 , but the measurement is more difficult since the decay chain

$$D^{*+} \rightarrow D^+\pi^0$$

includes a low momentum π^0 for which the experimental acceptance is small. Moreover, the lowest multiplicity, all charged tracks D^+ decay is in $K^-\pi^+\pi^+$, so three prongs must be measured, instead of two, and this increases the combinatorial background.

The $D^{*+} - D^+$ mass difference obtained by MARK II^[83] is shown in Fig. 16

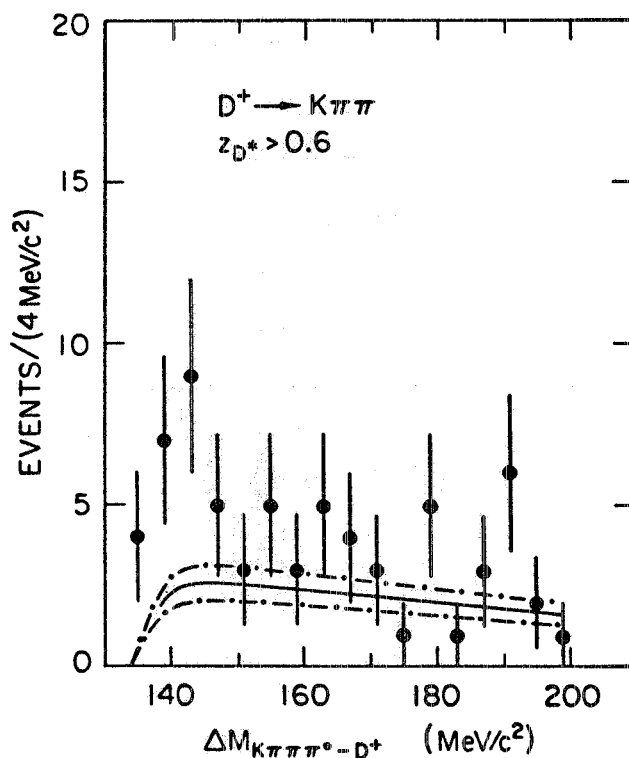


Fig 16: $D^{*+} - D^+$ Mass Difference (MARK II)

The region 135 - 146 Mev/c² is considered D^{*+} signal. There are 23 events in this ΔM range, with a background estimated at 5.7 ± 3.6 , a B feed-down of $(3 \pm 2)\%$ and a $(14 \pm 6)\%$ contamination from D^{*0} to $D^0 \pi^0$ decays; the distribution of the proper decay time is shown in Fig. 17.

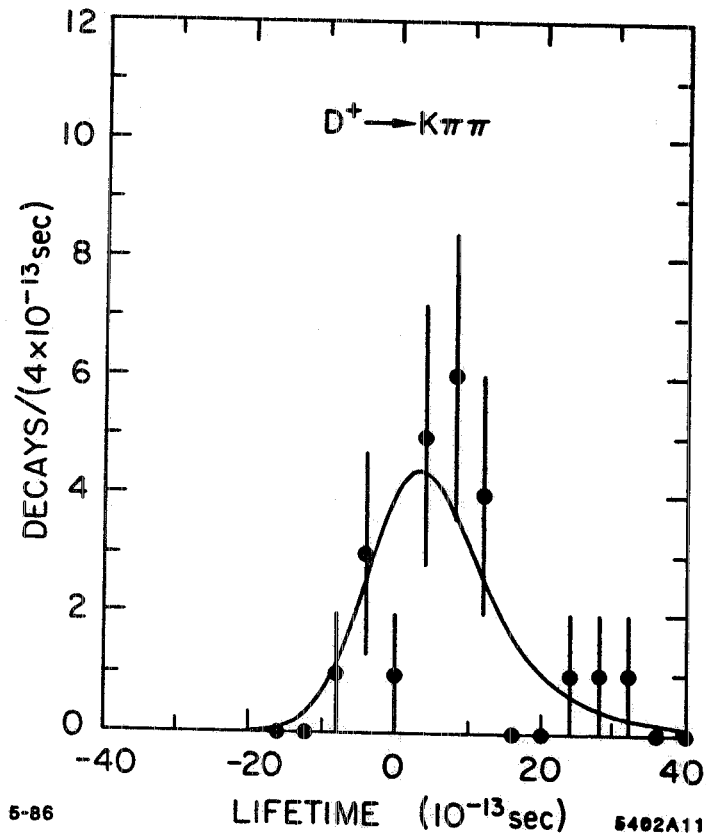


Fig 17: D^+ proper time distribution (MARK II)

The maximum likelihood fit, taking into account all corrections, yields:

$$\tau_{D^+} = (8.9^{+3.8}_{-2.7} \pm 1.3) \times 10^{-13} \text{ s}$$

this leads to a D^+ / D^0 lifetime ratio for the MARK II experiment of

$$\frac{\tau_{D^+}}{\tau_{D^0}} = 1.9^{+0.9}_{-0.6} \pm 0.3$$

With a similar analysis , based on a sample of 247 D^+ 's and a background evaluated at 30%, CLEO finds, as a preliminary result^[34]

$$\tau_{D^+} = (11.4 \pm 1.6 \pm 1.0) \times 10^{-13} \text{ s}$$

and

$$\frac{\tau_{D^+}}{\tau_{D^0}} = 2.33 \pm 0.50$$

Very recently the HRS group has reported^[35] a preliminary result on D^+ lifetime which uses a different technique: given its superior momentum resolution, HRS is able to identify the D^+ directly in the $K^-\pi^+\pi^+$ invariant mass distribution, using the cut in z ($z_{D^+} \geq 0.5$) and requiring well measured tracks and a good vertex χ^2 . The D^+ signal, shown in Fig. 18 , consists of 114 events over a background of 390 events.

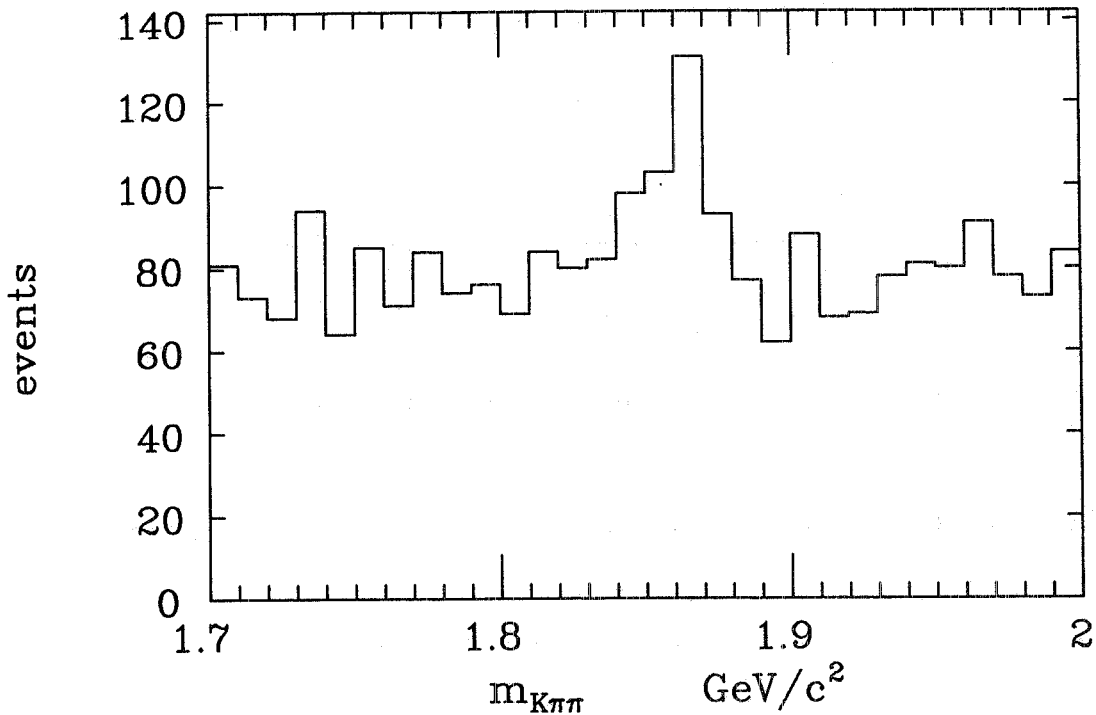


Fig 18: $K\pi\pi$ invariant mass distribution (HRS)

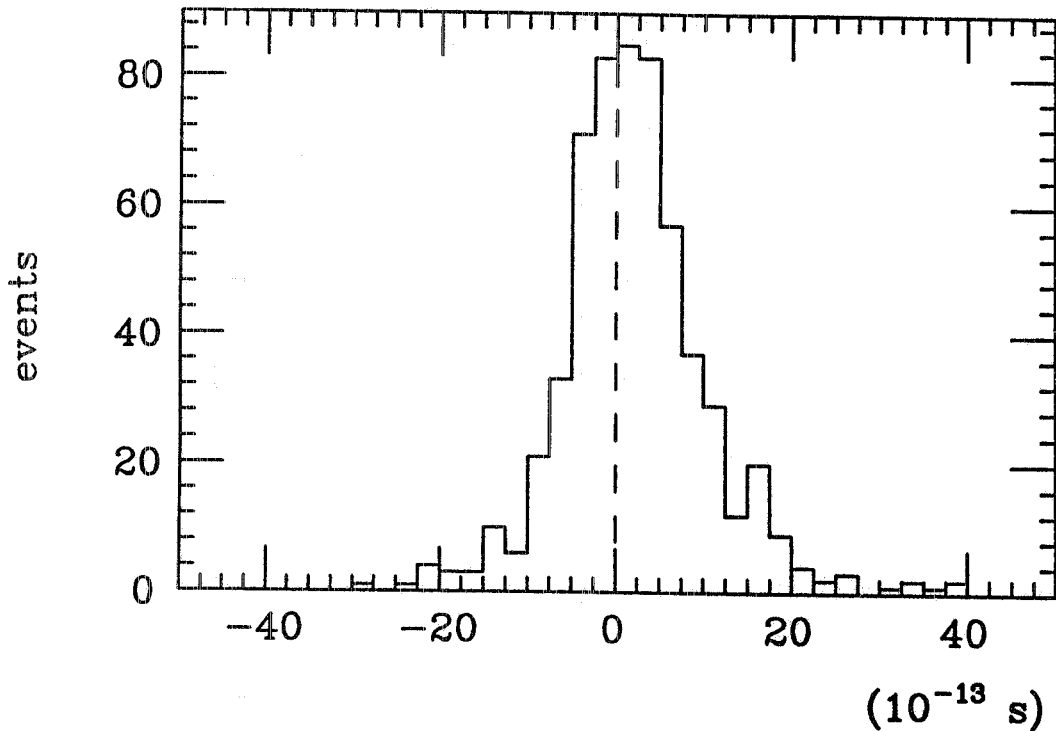


Fig 19: Decay time distribution for the D^+ signal region (HRS)

The proper time distribution in Fig. 19 is obtained from the measured decay path and momentum of the $K\pi\pi$ system in the signal region.

The lifetime after background correction (from track combinations in the signal side bands) is quoted to be:

$$\tau_{D^+} = (8.1 \pm 1.2 \pm 1.6) \times 10^{-13} \text{ s}$$

The summary of the world results for D^+ is reported in Table III and in Fig. 20 ; the agreement is satisfactory, given the wide variety of detectors and analysis techniques, acceptances, backgrounds, etc.

The average value is

$$\langle \tau_{D^+} \rangle = (10.1 \pm 0.4) \times 10^{-13} \text{ s}$$

TABLE III

D^+ Lifetime measurements

Experiment	# Decays	D^+ Lifetime (10^{-13} sec)	$\tau (D^+) / \tau (D^0)$
MARKII	17	$8.9^{+3.8}_{-2.7} \pm 1.3$	$1.89 \pm .9$
HRS	114	$8.1 \pm 1.2 \pm 1.6$	$1.93 \pm .50$
CLEO	247	$11.4 \pm 1.6 \pm 1.0$	$2.33 \pm .50$
SHF	48	$8.6 \pm 1.3^{+0.7}_{-0.3}$	$1.41 \pm .3$
Na-16	15	$8.4^{+3.5}_{-2.2}$	2.05 ± 0.9
Na-27	147	$10.6^{+1.3}_{-0.9}$	2.52 ± 0.37
Na-18	7	$6.3^{+4.9}_{-2.3} \pm 1.5$	1.54 ± 1.0
E-531	23	$11.1^{+4.4}_{-2.9}$	2.58 ± 0.92
WA-58	27	$5.0^{+1.5}_{-1.0} \pm 1.9$	1.39 ± 0.51
Na-1	98	$9.5^{+3.1}_{-1.9}$	2.2 ± 0.9
Na-11	28	$10.6^{+3.6}_{-2.4} \pm 1.6$	2.9 ± 1.0
Na-11	69	$11.2^{+1.6}_{-1.3} \pm 0.8$	3.0 ± 0.8
ACCMOR	42	$9.8^{+1.9}_{-1.5}$	2.51 ± 0.62
E-691	480	$10.9^{+0.8}_{-0.7} \pm 0.6$	2.48 ± 0.2

If one believes that the *world average* value is better than each measurement, the best estimate for the ratio of the D^+ to the D^0 lifetime is

$$\frac{\langle \tau_{D^+} \rangle}{\langle \tau_{D^0} \rangle} = 2.33 \pm 0.13$$

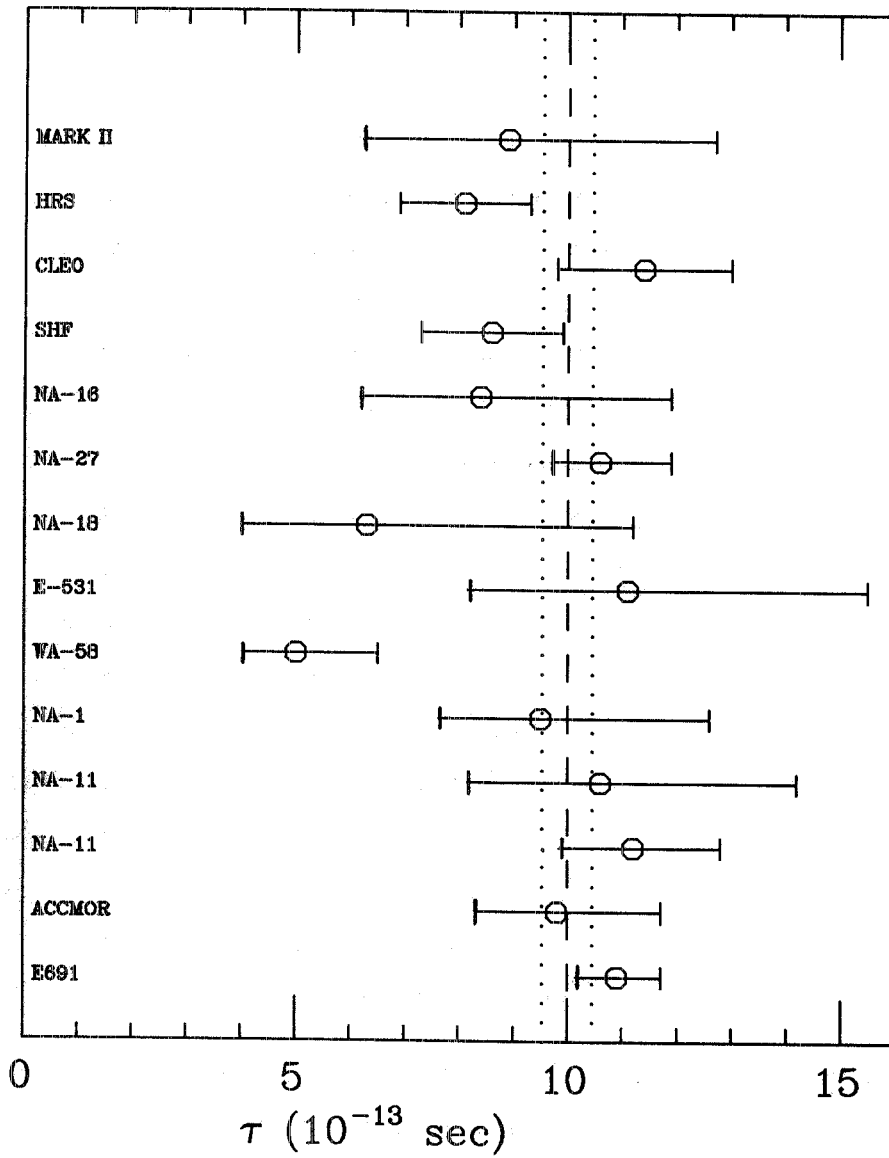


Fig 20: D^+ lifetime measurements

3.5 THE F^+ LIFETIME

The lifetime of the F^+ meson is of special interest because it could help in sorting out the possible explanations of the large difference in the lifetimes of the D^0 and D^+ mesons. Experimentally F^+ identification is more difficult than that of the D mesons: F's have been elusive particles for several years, in spite of the efforts of the experimenters; it was only in 1983 that CLEO^[36] discovered the F^+ in the $\phi\pi^+$ decay mode. The mass difference between F^* and F^+ is only 50 Mev, thus the transition can only proceed via the emission of a photon and it is not possible to use the F^* 's decay chain in order to improve the signal to background ratio. The information on other F^+ channels is still scanty; it was only in 1985 that the first lifetime measurement in e^+e^- interaction was announced by the HRS collaboration^[37]. Previously only two measurements had been reported in the literature, one from E-531 in emulsions^[38], and one from Na-11^[39] using silicon microstrips. These results were both affected not only by low statistics, but also by the uncertainty in the F^+ assignment: due to ambiguities in kaon and proton identification, D^+ , F^+ , Λ_c^+ are undistinguishable in several cases. In the last year more preliminary results were presented by other e^+e^- experiments (CLEO^[40] and TASSO^[41]) and silicon detectors (ACCMOR^[42] and E-691^[43])

The method used by HRS is the following: Φ 's were selected by calculating the invariant mass of all pairs of oppositely charged tracks, in each multihadronic event, with $p > 500\text{Mev}/c$ and assuming the kaon mass.

Pairs with

$$1009.6 < M_{K^+K^-} < 1029.6\text{Mev}/c^2$$

were defined Φ candidates. A kinematical fit was then performed to a Φ mass and a $\chi^2 < 16$ was required. These Φ candidates, which comprised 49% of the Φ candidates, were then combined with all other charged particles, and the cut $z_{\Phi\pi} > 0.4$ was applied; more cuts were then imposed on the *quality* of the tracks and the $\Phi - \pi$ vertex.

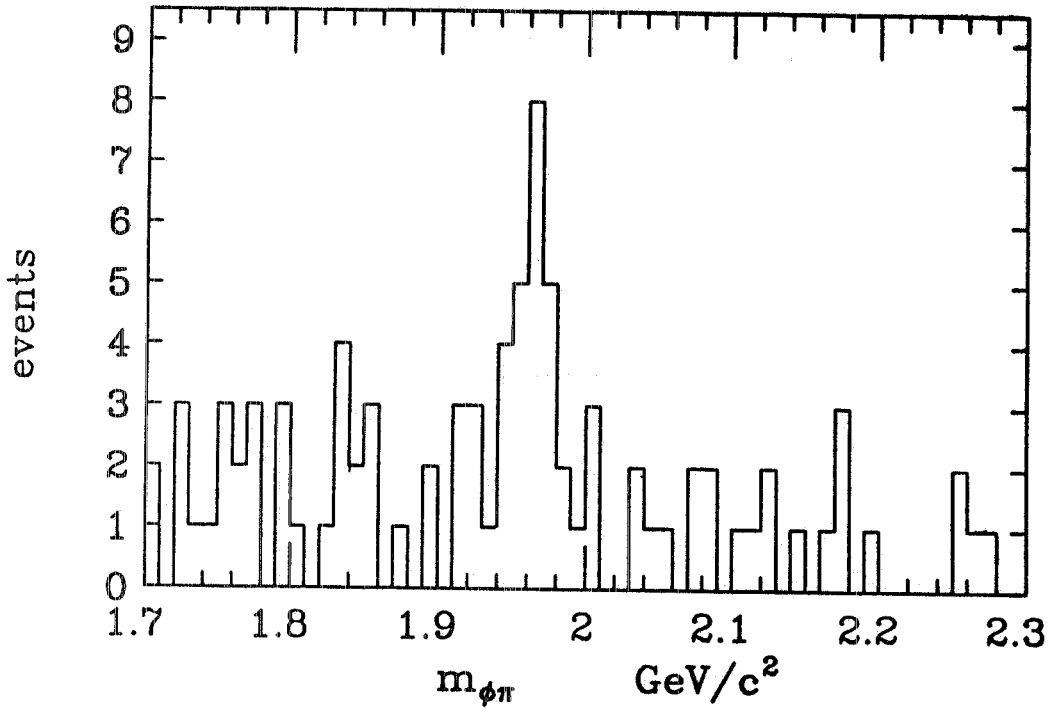


Fig 21: $\Phi\pi$ Invariant mass distribution (HRS)

A narrow peak with full width $20\text{MeV}/c^2$ is observed at $M_{\Phi\pi} = 1964\text{MeV}/c^2$ (Fig. 21); the F region is defined as $1940 < M_{\Phi\pi} < 1990\text{MeV}/c^2$ and contains 24 events which pass all analysis cuts.

The background is evaluated to be 24%, the feed-down from B decay 8%. The control sample was obtained from triplets of tracks with $M_{\Phi\pi}$ in the F^+ side bands and less restrictive cuts. From the measurement of the F^+ momentum and decay length, the proper decay time was calculated; a maximum likelihood fit to the distribution of the proper times (Fig. 22) yields:

$$\tau_{F^+} = (3.5^{+2.4}_{-1.8}) \times 10^{-13} \text{ s}$$

for the data, and an apparent lifetime

$$\tau_{\text{control}} = (-0.4 \pm 0.9) \times 10^{-13} \text{ s}$$

for the control sample. The systematic error was evaluated taking into account several possible sources of biases in the measurement; a linear sum of all the

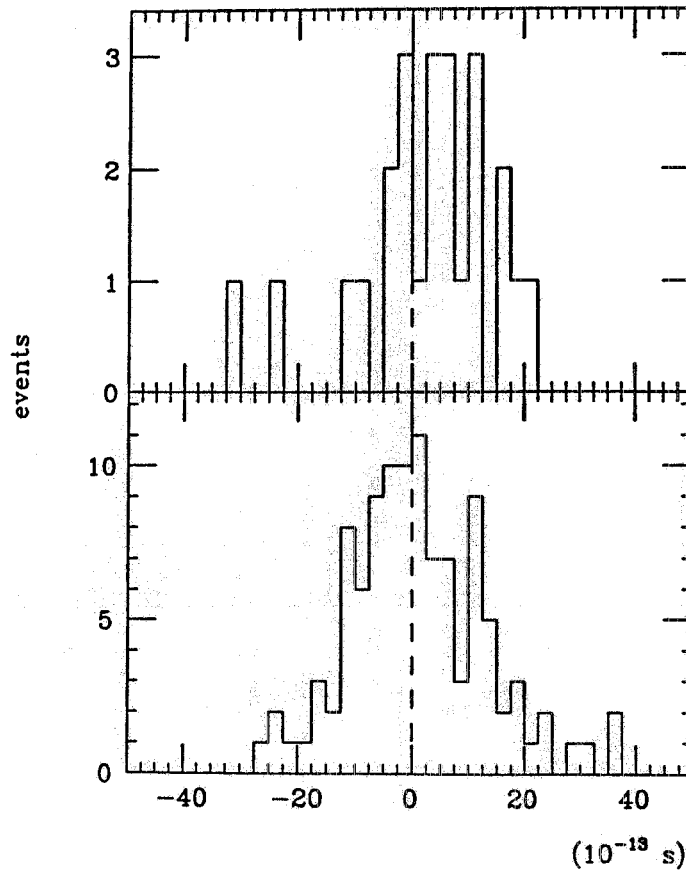


Fig 22: Decay time distributions for F^+ and background (HRS)

contributions gives an estimate of $\pm 0.9 \times 10^{-13}$.

Table IV and Fig. 23 summarize the present situation for the F^+ lifetime: the techniques used by the experiments have different characteristics: the emulsion and the silicon microstrips detectors have a superior vertex resolution which leads to a negligible error in the decay distance determination; event selections, however, are not lifetime independent and F^+ identification is not unambiguous. The e^+e^- experiments have a clean separation of F^+ from background, which is independent of the lifetime, but the error in the decay distance is comparable with the distance itself. Nevertheless, the agreement of the results is quite good, and the F^+ lifetime appear to be close to the D^0 's. the "world average" is:

$$\langle \tau_{F^+} \rangle = (3.7 \pm 0.4) \times 10^{-13} \text{ s}$$

TABLE IV

F^+ Lifetime Measurements

Experiment	Technique	Beam	#decays	F^+ Lifetime (10^{-13} sec)
HRS	Drift Ch.	e^+e^-	24	$3.5^{+2.4}_{-1.8} \pm 0.9$
CLEO	"	"	87	$4.6 \pm 2.1 \pm 0.5$
TASSO	"	"	7	$3.4^{+2.9}_{-1.6} \pm 0.7$
E-531	Emulsion	ν Interaction	6	$2.6^{+1.6}_{-0.9}$
NA-11	Silicon Det.	Hadroproduction	12	$3.1^{+1.2}_{-0.8} \pm 0.8$
ACCMOR	"	"	10	$3.9^{+0.6}_{-0.5}$
E-691	"	Photoproduction	35	$4.2^{+1.0}_{-0.8}$

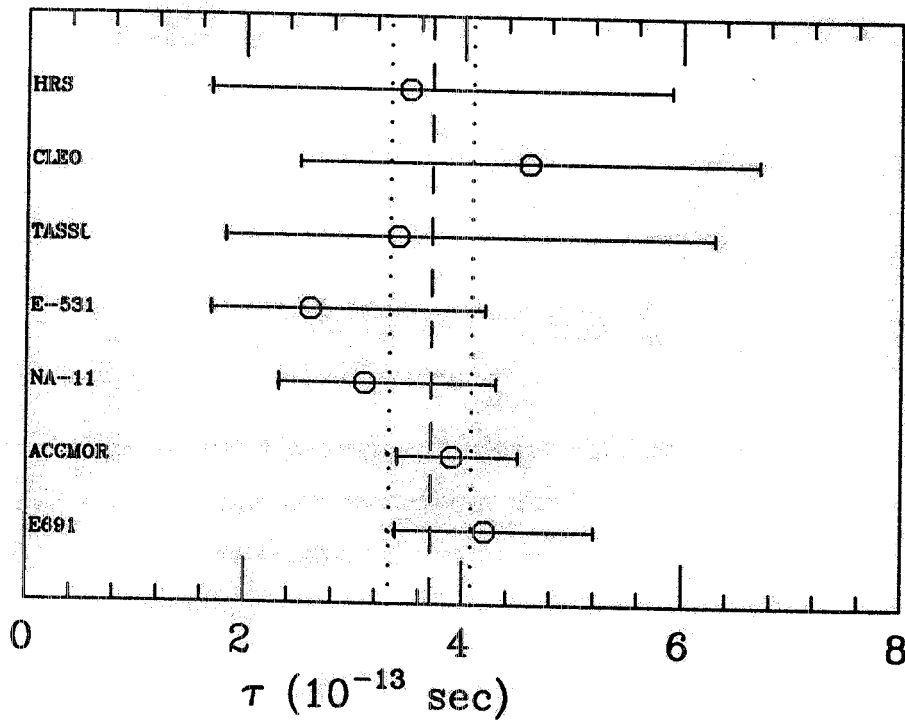


Fig 23: F^+ Lifetime Measurements

3.6 SUMMARY

The charmed mesons lifetimes have been measured by a large number of experiments, with different techniques and systematics. The overall picture is now quite consistent and the most important point is that the D^+ lifetime is $\approx 1\text{psec}$, and is approximately a factor two longer than that of the D^0 and the F^+ . The absolute value is close to the one predicted by the theory, but the discrepancy between D^0 and D^+ lifetimes indicates that the Spectator Model is not adequate to describe c decay.

Using the world's averages of each lifetime we have

$$\frac{\langle\tau(D^+)\rangle}{\langle\tau(D^0)\rangle} = 2.3 \pm 0.13$$

to be compared to the recent MARK III result^[44] on D 's semileptonic branching ratios:

$$\begin{aligned} Br(D^0 \rightarrow e^+ X) &= (7.5 \pm 1.1 \pm 0.4)\% \\ Br(D^+ \rightarrow e^+ X) &= (17.0 \pm 1.9 \pm 0.7)\% \end{aligned}$$

$$\frac{Br(D^+ \rightarrow e^+ X)}{Br(D^0 \rightarrow e^+ X)} = 2.3^{+0.5}_{-0.4} \pm 0.1$$

The fact that the lifetimes and the branching ratios are in the same ratio confirms that the D^0 and D^+ semileptonic widths are the same, within the errors. Spectator models predict equal semileptonic branching ratios, in a range from 13% to 19% depending on how QCD corrections are calculated.

The D^0 result is clearly smaller, implying that D^0 's hadronic decays are enhanced by other (non spectator) mechanisms. No definite conclusions can be drawn for the D^+ : the lifetime is not inconsistent with the spectator model, but the range of the theoretical previsions is too broad to exclude other effects. Several models have been proposed, which either enhance D^0 or suppress D^+

hadronic channels. One suggested mechanism is the so called *color mixed* diagrams, which for the D^0 leads to different final states than the usual spectator diagram, while for the D^+ leads to the same final quark states, and therefore could produce destructive interference, suppressing D^+ hadronic decays. In order to produce a physical state, the color of the quark from the W decay should match that of the light quark, this produces a factor 3 reduction in the amplitudes; QCD effects were expected to suppress these diagrams by a larger factor, but color suppression is not confirmed by the measurements of D branching ratios; for example $D^0 \rightarrow \bar{K}^0 \pi^0$ and $D^+ \rightarrow \phi \pi^+$ are not as small as expected.

Non spectator models have also been proposed, which contribute to D^0 and F^+ hadronic decays, and not to D^+ . Several possible diagrams are shown in Fig. 24. It has been suggested^[46] that the W exchange and W annihilation graphs, which were generally ignored because of helicity suppression at the light quark vertex $((m_q/m_c)^2)$, could proceed at a relatively high rate for gluons effects. Decays with no u quark in the final state, such as $D^0 \rightarrow \bar{K}^0 \phi, \bar{K}^0 K^0$, or $\bar{K}^{*0} K^0$ should be examples of W exchange mechanism. Measurements of these modes, however, are not precise enough to discriminate between models. Similarly, annihilation graphs are Cabibbo suppressed for the D^+ and allowed for D^0 and F^+ . Recently another mechanism has been suggested^[46], i.e. the emission and reabsorption of a W-boson, by which the charmed meson turns itself into a pair of light quarks; these graphs again would contribute to D^0 and F^+ but not to D^+ decays. To fully understand the pattern of the weak decays of charmed mesons a more detailed investigation of the hadronic modes is clearly necessary, both experimentally and theoretically.

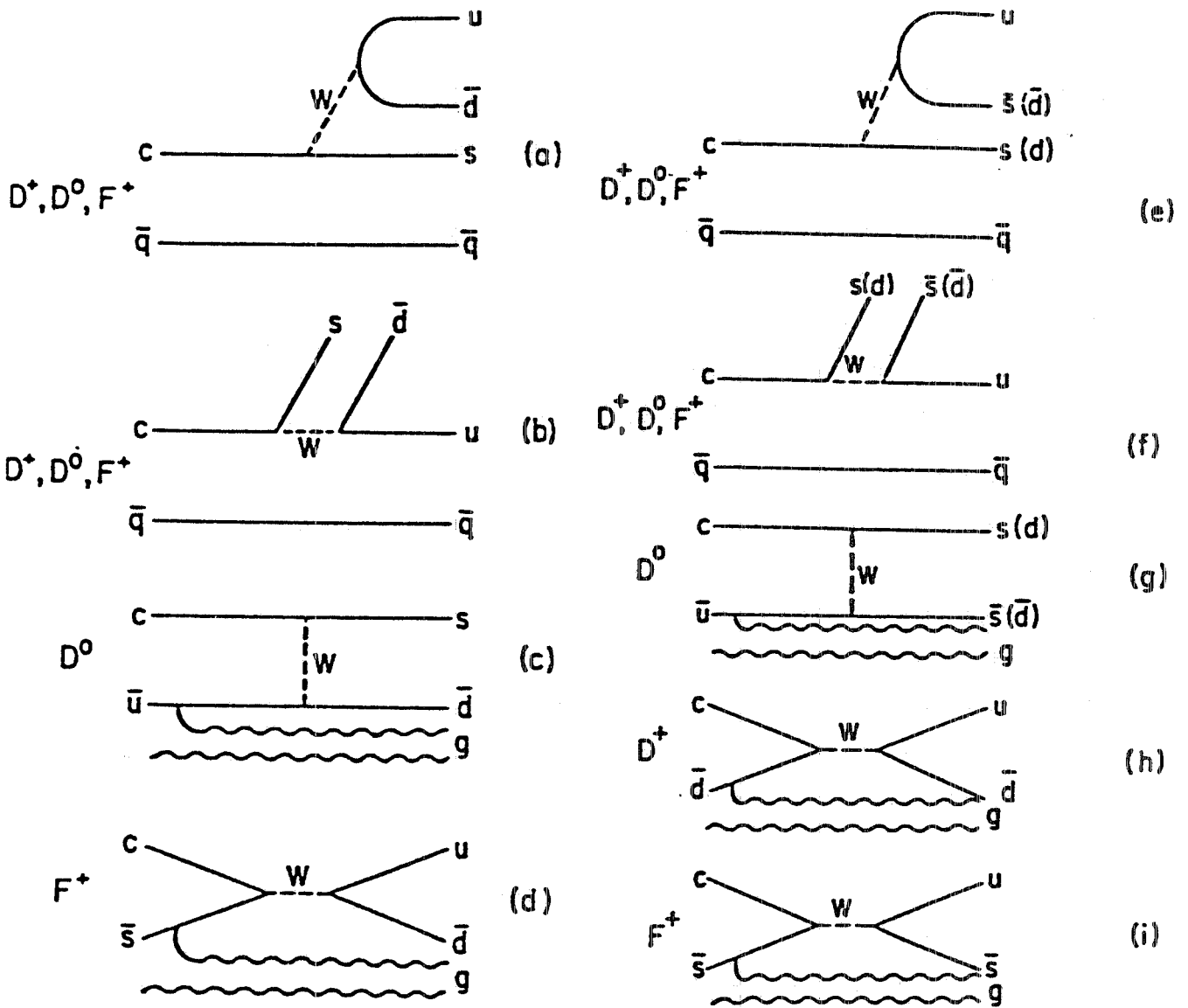


Fig 24: Diagrams for charmed mesons decay :

(a-d) are Cabibbo favored and (e-i) are Cabibbo suppressed.

(a),(b),(e),(f) are spectator quark processes, but (b) and (f) are color mixed.

(c), (g) are W-exchange, (d), (h), (i) are W-annihilation graphs.

Gluons are indicated for non-spectator processes to remove helicity suppression

4. b - LIFETIME

4.1 B DECAY AND THE MIXING MATRIX

The importance of the B particles lifetime stems from the fact that the b quark can only decay into a c or a u , which are members of different quark *generations*. If we consider the 3 quark doublets

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

the b is an a position similar to the s : B's are therefore as important to understand heavy quarks physics as kaons were for the light quarks. In the early sixties, the study of K decays played an important role in the formulation of the weak theory; it was observed that the quark states to which the intermediate bosons couple are mixtures of the physical states, and the mixing is characterized by one rotation angle, the Cabibbo angle θ_c .

In a theory with 3 doublets the mixing of quark states is given by a 3×3 unitary matrix V

$$\begin{vmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{vmatrix}$$

which can be parametrized with 3 angles and one phase. The amplitude of the transition from quark i to quark j is given by $|V_{ij}|^2$.

Kobayashi and Maskawa^[47] suggested this extension of the Cabibbo theory to a 6 quarks model , and also noted that the phase can be related to CP violation. The parametrization of this *mixing* matrix is not unique; a convenient form has been proposed by Maiani^[48] :

$$\begin{vmatrix} c_{\beta}c_{\theta} & c_{\beta}s_{\theta} & s_{\beta} \\ -c_{\gamma}s_{\theta} - s_{\gamma}s_{\beta}c_{\theta}e^{i\delta} & c_{\gamma}c_{\theta} - s_{\gamma}s_{\beta}s_{\theta}e^{i\delta} & s_{\gamma}c_{\beta}e^{i\delta} \\ -c_{\gamma}s_{\beta}c_{\theta} + s_{\gamma}s_{\theta}e^{-i\delta} & -c_{\gamma}s_{\beta}s_{\theta} - s_{\gamma}c_{\theta}e^{-i\delta} & c_{\gamma}c_{\beta} \end{vmatrix}$$

where c indicates cosine and s sine; θ, γ, β are the 3 angles, θ being very close to the familiar Cabibbo angle; δ is the phase. To the first order in all the angles, this matrix assumes the very simple form:

$$\begin{vmatrix} 1 & \theta & \beta \\ -\theta & 1 & \gamma \\ -\beta & -\gamma & 1 \end{vmatrix}$$

and the angles have a simple physical meaning: γ indicates the mixing of second and third generations, β the coupling between first and third.

In absence of experimental information on B decays, only loose limits from unitarity could be derived for β and γ : $\sin\beta < 0.09$ and $\sin\gamma < 0.78$; the b quark lifetime depends in principle from both V_{ub} and V_{cb} :

$$\tau_b = \tau_{\mu} \times \frac{1}{a|V_{ub}|^2 + b|V_{cb}|^2}$$

but since V_{ub} is small, it is an almost direct measurement of V_{cb} , or $\sin\gamma$. Mixing angles are free parameters in the theory : prior to measurement it was generally assumed $\sin\gamma \approx \sin\theta = 0.22$, and a lifetime $\approx 10^{-14}$ sec was expected for the b. It came therefore as a surprise the first determination of b particles lifetime (MAC , 1983) which gave a result of about one picosecond.

4.2 THE EXPERIMENTAL METHOD

Measuring the b-lifetime is a real challenge for present e^+e^- experiments: production is less abundant (only 9% of the multihadronic events come from a $b\bar{b}$ pair), B mesons are not reconstructed, so their direction and momentum is unknown, both production and decay vertices are not seen .

The method originally used by MAC^[49] and MARK II^[50] to overcome these difficulties is the following: $b\bar{b}$ events are identified on a statistical basis, from the presence of a lepton with high transverse momentum respect to the thrust axis (lepton tag).

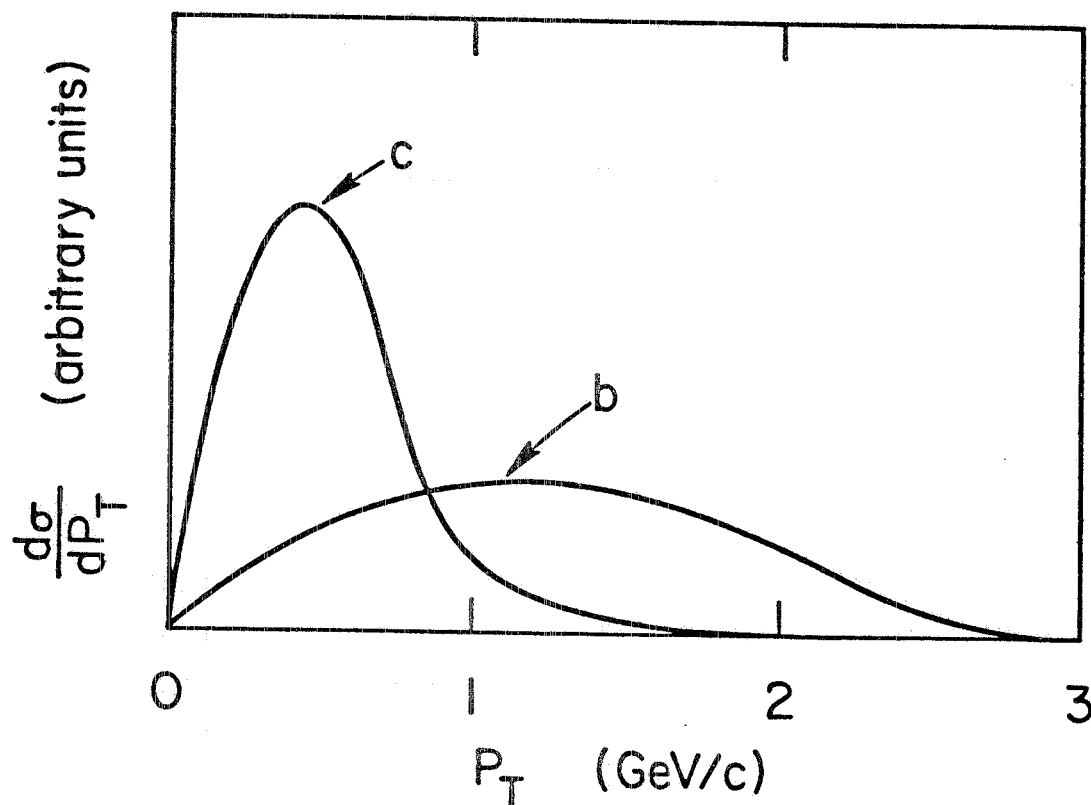


Fig 25: p_{\perp} distributions of leptons from c and b decay (MARK II Montecarlo)

The p_{\perp} distribution of leptons from B semileptonic decays is in fact harder than that from charm, and events with a lepton of $p_{\perp} > 1\text{GeV}/c$ constitute an *enriched* b sample, as can be seen in Fig. 25

The production vertex is approximated by the beam centroid and the B direction is assumed to be the same as the thrust axis, which is very close to the direction of the primary quarks. The impact parameter of the leptons (see Fig. 26) is then calculated, and its distribution related to the lifetime:

$$\langle \delta \rangle = \langle l_0 \sin \psi \rangle = \langle \beta \gamma \sin \theta \sin \psi \rangle c \tau \approx \alpha \tau$$

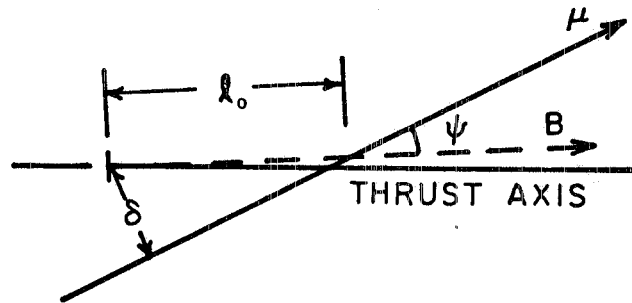


Fig 26: Impact parameter of a μ ; the B direction is unknown

The sign of δ is defined positive when the lepton appears to be emitted in the forward direction by a particle travelling from the interaction point along the thrust axis. In case of zero lifetime, the average impact parameter would be zero, because the sign would be randomly assigned, and the distribution would be a gaussian with σ equal to the resolution.

For a positive lifetime the impact parameter distribution would have the characteristic exponential shape; in case of perfect resolution the δ distribution for a 1 psec lifetime would be that of Fig. 27 (a). The effect of the error σ_{δ} in the

measure of δ is that the exponential shape is folded with a gaussian of σ equal to the error; for $\sigma_\delta = 200\mu m$ the result is shown in Fig. 27 (b).

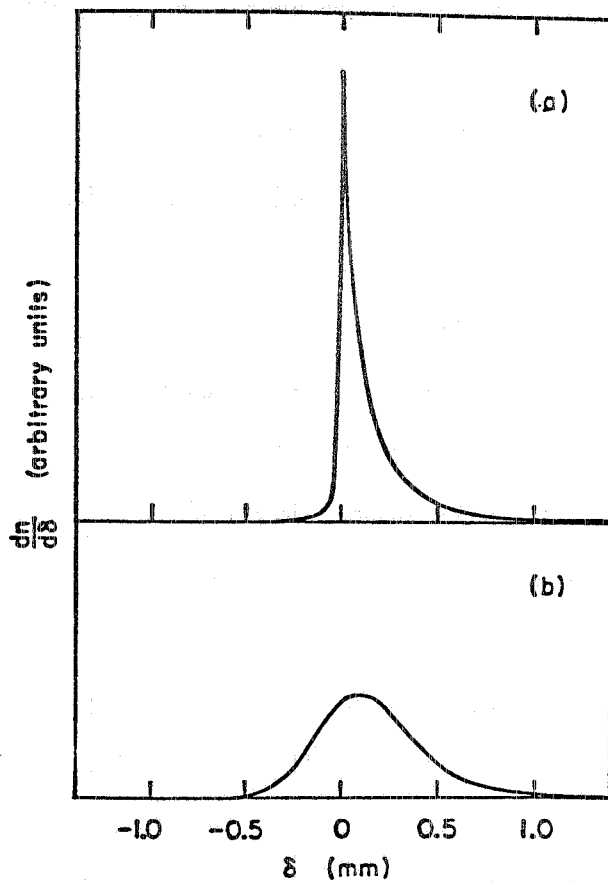


Fig 27: Impact parameter distribution for 1 psec lifetime:

(a) Perfect resolution. (b) $\sigma_\delta = 200\mu m$

For most b- lifetime experiments the measurement error is considerably larger than the effect to be measured, and the impact parameter distribution appears as a gaussian; because of the positive lifetime, the mean value of the distribution is positive; given enough statistics, even a small shift from zero can be measured accurately, as we have seen in the case of the MAC's measurement of the τ lifetime.

The fact that the thrust axis is used instead of the true B direction, introduces a dilution of the effect of a finite lifetime, because in some cases the sign assignment is wrong; the correction is included in the value of α which is obtained by Montecarlo studies.

The steps followed by a typical b-lifetime analysis are:

- electrons and/or muons are identified in multihadronic events from 1-photon annihilation.

- the thrust axis direction is calculated

- the lepton's p_{\perp} is required to be $> 1\text{Gev}/c$ (MAC uses $> 1.5\text{Gev}/c$) and eventually other cuts are applied to obtain a clean b- sample.

- the impact parameter δ and its error σ_{δ} are calculated.

- only events with well measured δ are used; usually a loose cut on σ_{δ} is applied.

- the impact parameter distribution is studied in order to extract the lifetime value. this implies extensive Montecarlo studies and a fitting or averaging procedure .

- systematic effects are carefully studied, by Montecarlo or using hadronic tracks in non-b events, which could bias the measurement. τ lifetime is often used as a calibration.

- the results obtained refer to the average lifetime of the mixture of B particles present in the sample, whose composition is not known.

4.3 THE RESULTS

Several experiments, at PEP and PETRA, have measured the b lifetime; MAC and MARK II have updated their earlier results using additional data and refined analysis; MAC has also an improved tracking. I will give now an overview of the experiments and a somewhat more detailed description of the new MAC analysis^[51] which exploits the superior resolution of the Vertex Chamber.

MAC .The data samples for b lifetime analysis consist of events prior to the addition of the vertex chamber (corresponding to an integrated luminosity of $220 pb^{-1}$) and events collected in the more recent runs ($94pb^{-1}$), with the VC information. The impact parameter method is used and the event selection is based on the lepton tag: electron and muons with $p > 2.0Gev/c$ and $p_{\perp} > 1.5Gev/c$. To further clean the b sample, the thrust axis is required to be at an angle between 30° and 150° respect to the beam direction; this cut ensures that the energy deposition of the event is well measured. The thrust of the event is required to be > 0.72 in order to eliminate quasi-isotropic events, where the thrust axis is poorly defined. Muons are selected by the highly redundant MAC muon system, with hadron punch-through reduced to $< 5\%$; electrons are identified by the match of a charged track with a shower in the electromagnetic calorimeter whose transverse and longitudinal energy deposition is consistent with an electromagnetic cascade. After all cuts are applied, the fraction of b events is $63 \pm 5\%$ for the muon tagged sample, and $62 \pm 5\%$ for the electron tags. To increase the statistics in the lifetime measurement, all the well measured tracks are used for the impact parameter measurement, not only the leptons. The pre-VC data contain 1402 such tracks which give a mean value of δ of $154 \pm 20\mu$; the VC data sample consists of 441 tracks whose impact parameter distribution is shown in Fig. 28 . The mean value is $129 \pm 14\mu$.

In order to extract the lifetime, $\langle \delta \rangle$ can be expressed as:

$$\langle \delta \rangle = f_b \delta_b + f_c \delta_c + f_{bg} \delta_{bg}$$

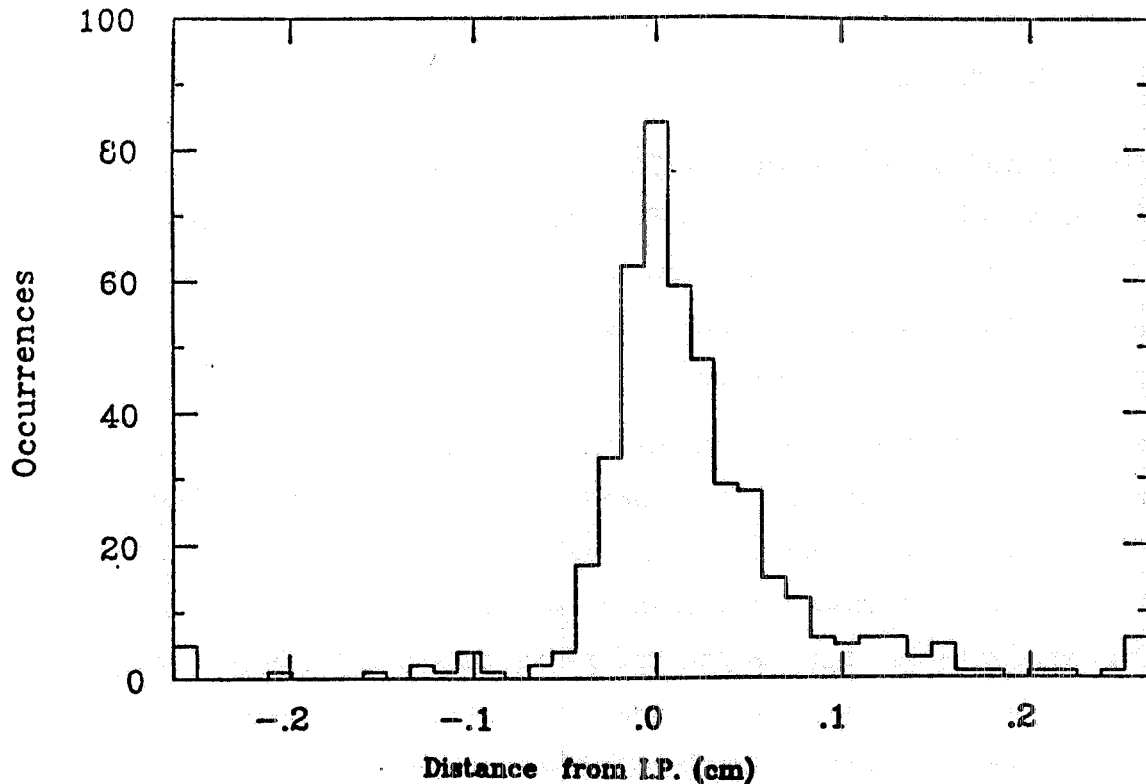


Fig 28: Impact parameter distribution of the b-enriched sample (MAC, VC data)

where f 's represent the fractions of b, c and background and δ 's are the corresponding contributions to $\langle \delta \rangle$; $f_b, f_c, f_{bg}, \delta_c, \delta_{bg}$ are determined by Montecarlo, and δ_b is calculated from the measured $\langle \delta \rangle$. The combined lifetime $\tau_b = \alpha \delta_b$, from both event samples is:

$$\tau_b = (1.16 \pm 0.16 \pm .17) \times 10^{-12} \text{sec}$$

the systematic error was determined after careful checks of the detector performance, the Montecarlo simulation and the analysis method; τ lifetime was used as a calibration and a large control sample of hadronic events (not tagged) was studied and found to give results in agreement with the corresponding Montecarlo events.

MARK II. Two measurements have been performed, the first uses the impact parameter method and is an update of the early analysis with increased statistics. The final b-enriched sample^[62] contains 282 events with a high p_{\perp} lepton, and has an estimated purity of 64%. Events with a lepton of $p_{\perp} < 1$ GeV/c constitutes the c-enriched sample. The two impact parameter distributions are shown in Fig. 29.

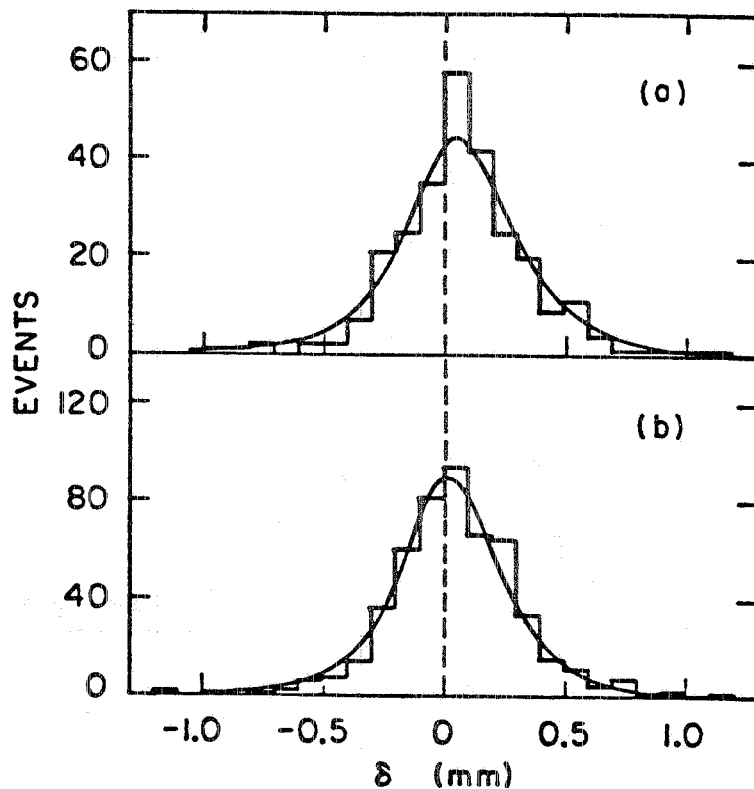


Fig 29: Leptons impact parameter distribution (MARK II)

(a) b-enriched sample, (b) c-enriched sample

The average impact parameter is $(80 \pm 17)\mu$ and $(59 \pm 12)\mu$ respectively for the two p_{\perp} regions. The lifetime is calculated with a maximum likelihood fit:

$$\tau_b = (0.85 \pm 0.17 \pm 0.20) \times 10^{-12} \text{sec}$$

The second method uses the same sample : each event is divided in two jets by a plane perpendicular to the thrust axis and a vertex is formed from well measured tracks (minimum 3 required) of each jet. The lifetime is determined by a maximum likelihood fit to the distribution of the distance of each vertex from the beam centroid (see Fig. 30).

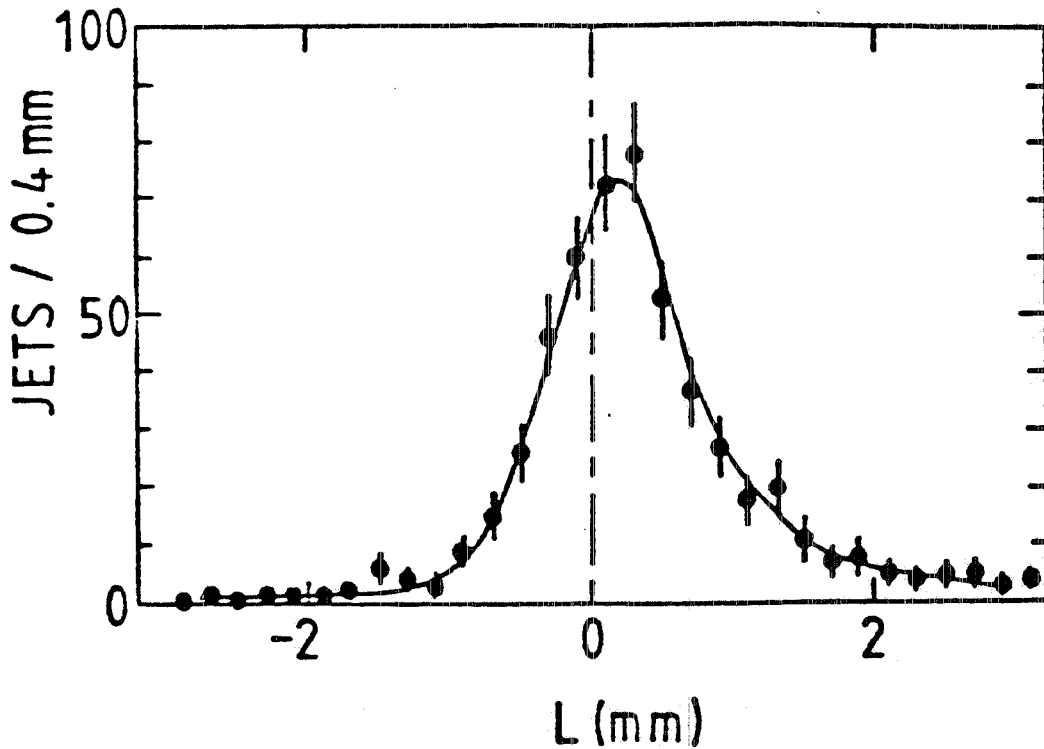


Fig 30: Path length distribution for lepton tagged $b\bar{b}$ jets (MARK II).

The result is:

$$\tau_b = (1.25_{-0.19}^{+0.26} \pm 0.50) \times 10^{-12} \text{sec}$$

the systematic error is bigger since this method relies more on Montecarlo modeling.

DELCO. The gas Čerenkov counters used by this detector provide an excellent electron identification which, in turn, allows the selection of a clean $b\bar{b}$ event sample (70% $b \rightarrow e$, 9% $b \rightarrow c \rightarrow e$, 17% $c \rightarrow e$ and only 4% background). Electrons are selected with momentum above 1.0 GeV /c and this lower p cut increases the opening angle for b decays, thus increasing the average impact parameter. The distribution for the b enriched sample ($p_{\perp} > 1\text{GeV}/c$) is shown in Fig. 31 ; the points indicate the data (the error bars are statistical only) and the smooth curve is a MonteCarlo calculation of the expected distribution based on $\tau_b = 1.17\text{psec}$ and $\tau_c = 0.64\text{psec}$.

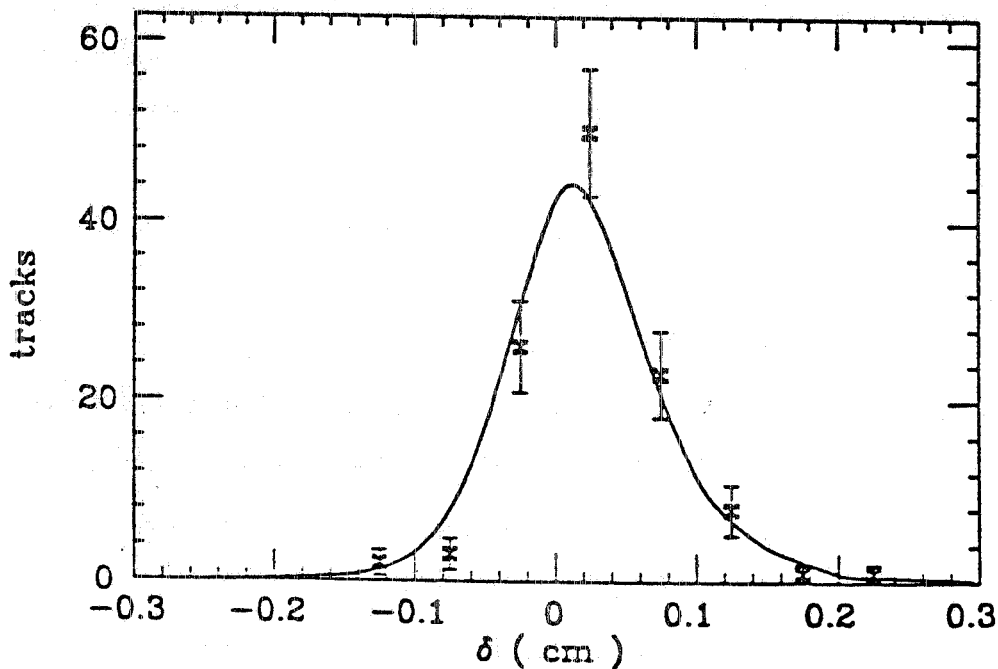


Fig 31: Impact parameter distribution for the b-enriched sample (DELCO)

The sample consists of 113 tracks and the average impact parameter is:

$$\langle \delta_b \rangle = 259 \pm 49 \mu$$

The c-enriched sample ($p_{\perp} < 1 \text{ GeV}/c$) consists of 449 tracks and :

$$\langle \delta_c \rangle = 146 \pm 28 \mu$$

The b lifetime is obtained^[53] from a maximum likelihood fit to the impact parameter of the 113 electron tracks :

$$\tau_b = (1.17_{-0.22}^{+0.27+0.27}) \times 10^{-12} \text{ sec}$$

JADE. This experiment uses the impact parameter of tracks produced in B decays with two analysis techniques for selecting events^[54]. One method uses a system of cuts to isolate a sample of B decay events of good purity; a maximum likelihood fit is performed on leptons δ distributions in order to determine the lifetime. The second method uses all events and a weighting technique to enhance the effect of B decay statistically: the weight is assigned on the basis of aplanarity and the presence of high p_{\perp} muons. The lifetime is derived by calculating the mean value of δ .

The first analysis yield a sample of 74 μ tracks and 25 e tracks with average impact parameter

$$\langle \delta_{\mu} \rangle = 282 \pm 78 \mu, \langle \delta_e \rangle = 457 \pm 107 \mu$$

These distributions are shown in Fig. 32 where the dashed lines are Gaussian fits with zero mean and the solid line is obtained using a B lifetime of 1.8 psec.

the maximum likelihood fit gives a combined value for the two samples of:

$$\tau_b = (1.76_{-0.38}^{+0.45}) \times 10^{-12} \text{ sec}$$

The second method is used as a check, since systematic errors are largely different; the result is in very good agreement but errors are larger, so the group quotes the previous one as JADE b lifetime value.

TASSO. $b\bar{b}$ event selection is based on event shape: events from B's decay have higher sphericity; this is also the case for 3-jets events. In order to distinguish between these two classes, each event was divided into 2 hemispheres, by a

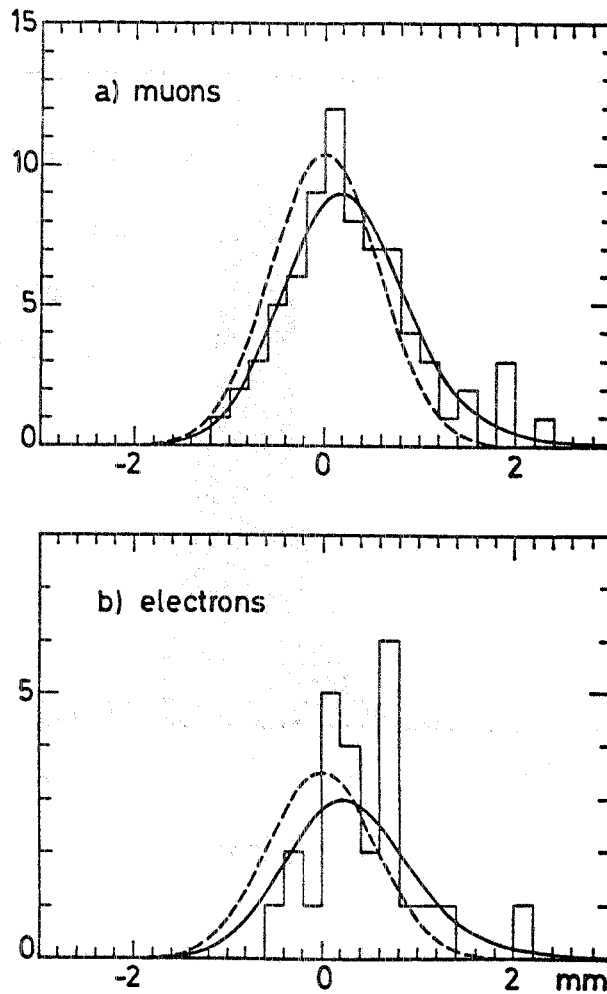


Fig 32: Impact parameter distribution of (a) muons, (b) electrons (JADE)

plane perpendicular to the thrust axis ,and the separate sphericities s_1 and s_2 of the two jets were calculated, in the respective rest frame A cut was then applied to their product:

$$s_1 \times s_2 > 0.1 \text{ defines } b \text{ enriched events}$$

$$s_1 \times s_2 > .04 \text{ defines } b \text{ depleted events}$$

From a Montecarlo simulation it was found that the b enriched sample contains 32% $b\bar{b}$,35% $c\bar{c}$, 33% light quark pairs. The impact parameter of all good quality tracks, with $p > 1\text{Gev}/c$ was used to determine the b-lifetime. The distribution for the B enriched sample shows a marked excess at positive values of δ compared to the B depleted sample (Fig. 33).

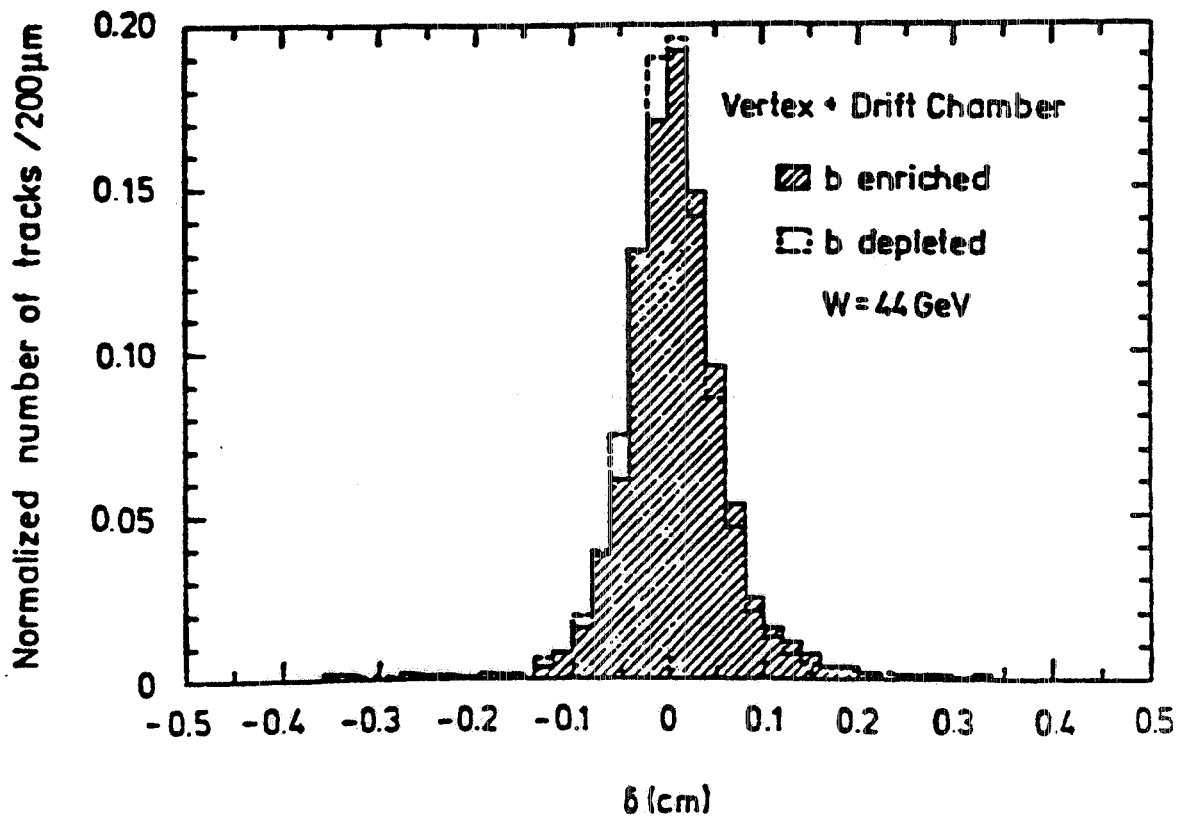


Fig 39: Distribution of the hadron impact parameter (Tasso)

It should be noted that this result refers to a mixture of B particles that could be different from that of the other experiments, since all events, not only semileptonic B decays are used. The b lifetime is quoted^[68] to be:

$$\tau_b = (1.57 \pm .32_{-0.34}^{+0.37}) \times 10^{-12} \text{sec}$$

the systematic error is dominated by the uncertainty in the $b\bar{b}$ fraction, due to the Montecarlo model dependence of the method.

4.4 SUMMARY AND IMPLICATIONS

b lifetime's measurements range actually from 0.8 and 1.8 psec, as summarized in Table V and plotted in Fig. 34 .

TABLE V

b Lifetime Measurements

Experiment	Method	Tracks used	Event sel.	b Lifetime (10^{-13} sec)
MAC (83)	Imp. Par.	μ, e	lepton p_{\perp}	$1.8 \pm 0.6 \pm 0.4$
MARKII (83)	"	"	"	$1.2^{+0.45}_{-0.3} \pm 0.3$
MAC (84a) ^[56]	"	"	"	$1.6 \pm 0.4 \pm 0.3$
MARK II (84a)	"	"	"	$0.85 \pm 0.17 \pm 0.21$
DELCO (84) ^[57]	"	e	"	$1.16^{+0.37+0.37}_{-0.34-0.34}$
MARKII (84b)	Vertex	all	"	$1.25^{+0.26}_{-0.19} \pm 0.5$
TASSO	Imp.Par.	all	ev.shape	$1.57 \pm .32^{+0.37}_{-0.34}$
JADE	"	μ, e	lepton p_{\perp}	$1.76^{+0.45}_{-0.38}$
MAC (85) ^[58]	"	"	"	$0.81 \pm 0.28 \pm 0.17$
DELCO (86)	"	e	"	$1.17^{+0.27+0.17}_{-0.22-0.16}$
MAC (86)	"	all	"	$1.16 \pm 0.16 \pm 0.17$

Systematic and statistical errors of these experiments are, however, large, so the results are not obviously inconsistent. If we calculate the weighted average of these measurements (which is not a correct procedure because some results are obtained from overlapping data samples) using statistical errors only, we obtain:

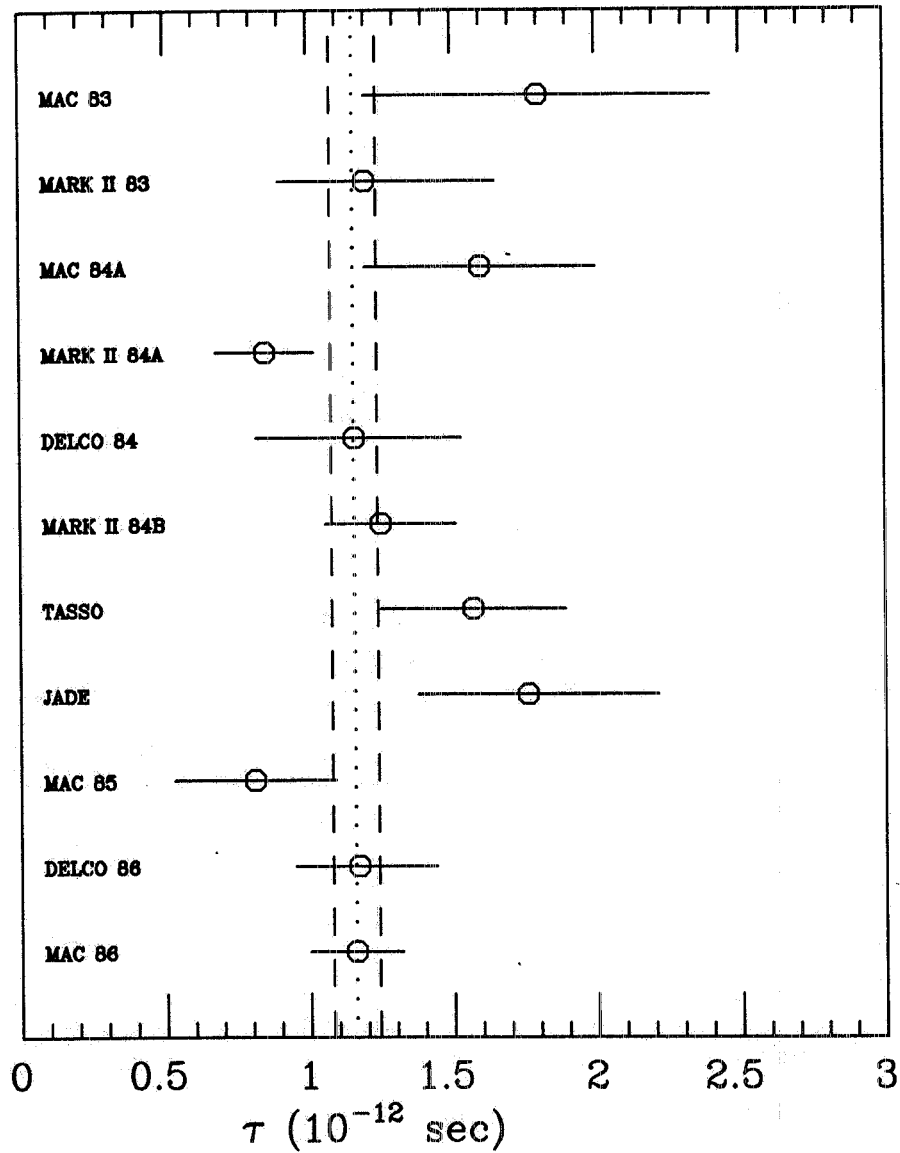


Fig 34: b- Lifetime Measurements.

$$\langle \tau_b \rangle = (1.15 \pm 0.08) \times 10^{-12} \text{sec}$$

We can use this *world average* as a guideline to derive the mixing angle γ ; the relation between b-lifetime and KM matrix elements is however somewhat model dependent since non spectator contributions and final state quark interactions enter in the calculation of the coefficients of $|V_{bc}|^2$ and $|V_{bu}|^2$. Moreover, there is

also a dependence from the quark masses. If we use the expression ^[59]

$$\tau_b^{-1} = \frac{G^2 m_b^5}{192\pi^3} (2.75|V_{bc}|^2 + 7.69|V_{bu}|^2)$$

with $m_b = 5\text{GeV}/c^2$ and $|V_{bu}| = 0$ we obtain:

$$\sin\gamma \approx |V_{bc}| = 0.053 \pm 0.007$$

We know that $|V_{bu}|$ is small since no evidence has been found yet for B decays not involving charmed mesons; an upper limit can be obtained from the study of the momentum distribution of the electrons from B's : the decay $B \rightarrow euX$ would produce a spectrum with end point farther then $B \rightarrow ecX$. This distribution has been studied at CESR and DORIS and found to be compatible with $B \rightarrow ecX$; the procedure to extract an upper limit to the ratio $|V_{bu}|/|V_{bc}|$ is again model dependent ^[60] and results may vary from 0.12 to 0.25, leading to an upper limit

$$\sin\beta \approx |V_{bu}| < 0.006 - 0.013$$

The overall picture that emerges from the b-lifetime measurement is the following:

$$\beta \ll \gamma \ll \theta$$

i.e. the coupling decreases with the generation number and the third quark doublet mixes with the second much less than the second does with the first. This explains why the Cabibbo theory seems to work so well: the heavier quarks have a small effect on the lighter ones and the 2×2 matrix of the *old* physics is almost unitary.

For the same reason present data do not impose any strong constraint on the top mass and do not shed any light on the possible existence of a fourth quark generation. The top's lifetime is expected to be very short ($10^{-17} - 10^{-18}\text{sec}$) and its decay should proceed via the cascade:

$$t \rightarrow b \rightarrow c \rightarrow s$$

since $V_{tb} \approx 1$ and the coupling to the light quarks is practically negligible.

CONCLUSIONS

The measurements of the lifetime of the heavy lepton τ and of the hadrons containing *heavy flavours* have been improving steadily in the last few years. All results on the τ and on the b lifetime come from e^+e^- experiments, while charmed mesons have been studied with a variety of techniques. The silicon strips detectors are at the moment the most powerful devices for measuring the charmed particles lifetime and the precision that these experiments will achieve in the near future will be difficult to match.

All results obtained fit nicely in the Standard Model of the electro-weak interactions; a great deal has been learned on the decay of heavy lepton and quarks, but many details remain to be understood. The spectator model is not adequate to describe charmed mesons decay and color suppression does not seem to be effective in charm decay. We do not know yet if non spectator models play an important role in b-decay since the separate lifetimes of B^0 and B^- have not been measured yet.

Looking ahead, a new generation of experiments will soon start operation at the new e^+e^- machines TRISTAN, SLC and LEP, and a new energy range will be open to investigation. The new detectors now being built are much more powerful than the previous ones and will be equipped with sophisticated solid state vertex detectors. Especially suited to lifetime measurements will be the SLC with its $2\mu^2$ beam interaction area and slow repetition rate. The next challenge to experimenters will be the individual measurement of the B^0 and B^- lifetimes, a key to b decay understanding.

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