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MEASUREMENTS OF HEAVY QUARK AND LEPTON LIFETIMES*

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1. Introduction

The PEP/PETRA energy range has proved to be well-suited for the study of the lifetimes of hadrons containing the b and c quarks and the tau lepton for several reasons. First, these states comprise a large fraction of the total interaction rate in e^+e^- annihilation and can be cleanly identified. Second, the storage rings have operated at high luminosity and so produced these exotic states copiously. And finally, thanks to the interplay of the Fermi coupling strength, the quark and lepton masses, and the beam energy, the expected decay lengths are in the 1/2 mm range and so are comparatively easy to measure.

This pleasant coincidence of cleanly identified and abundant signal with potentially large effects has made possible the first measurements of two fundamental weak couplings, $\tau \rightarrow \nu_\tau W$ and $b \rightarrow cW$. These measurements have provided a sharp test of the standard model and allowed, for the first time, the full determination of the magnitudes of the quark mixing matrix.

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This paper will review the lifetime studies made at PEP during the past year. It begins with a brief review of the three detectors, DELCO, MAC and MARK II, which have reported lifetime measurements. Next it discusses two new measurements of the tau lifetime, and briefly reviews a measurement of the D^0 lifetime. Finally, it turns to measurements of the B lifetime, which are discussed in some detail.

2. Detectors

The DELCO,[1] MAC[2] and MARK II[3] detectors have complementary strengths for lifetime studies. The DELCO device is an open geometry magnetic detector with segmented Čerenkov counters and accurate charged particle tracking close to the interaction point. It has a total of 16 drift chamber layers, giving a momentum resolution of $\Delta p/p^2 = .02$ (p in GeV/c). Tracks can be extrapolated to the interaction point with a resolution of 280 μ. Electrons can be identified over 52% of the solid angle with a combination of tracking, Čerenkov and shower counter information. The identification is very clean, thanks to the Čerenkov signal; hadron misidentification is at the 0.1% level. The MAC detector has much better solid angle acceptance and identifies both electrons and muons, but discriminates less well against hadronic backgrounds. Electrons are identified over 72 % of the solid angle by combining charged tracking information with the responses of lead-PWC and iron-PWC calorimeters. Hadronic punch-through is $1/2 - 1$ % . Muons are identified by matching tracks which survive the magnetized iron absorber with tracks in the central detector. Between 1 – 2 % of hadronic tracks simulate muons because of punch–through or decay. The MAC central detector has 10 drift chamber layers located between 12 and 45 cm from the beams. This permits modest momentum resolution ($\Delta p/p^2 = 0.065$) and 400 μ extrapolated track resolution for stiff tracks. The MARK II detector, a large multipurpose spectrometer, is especially suited for lifetime studies because of its high precision inner tracking chamber, or vertex detector. The vertex detector is built directly outside a Beryllium beam pipe, which minimizes multiple Coulomb scattering, and has an extrapolated track resolution of 100 μ. MARK II has a total of 23 drift chamber layers, including 7 in the vertex detector, which give a momentum resolution of $\Delta p/p^2 = 0.01$. Electrons are identified over 65 % of the solid angle with a lead–liquid argon calorimeter. Muons are selected over 45 % of the solid angle with a steel absorber/proportional tube sandwich. Roughly 1 % of hadrons are misidentified as electrons, and 1 – 2 % as muons. Where vertexing or impact parameter resolution are of central importance, as in the tau lifetime measurements, the superior resolution of the MARK II detector is a clear advantage. In the B lifetime studies, however, clean lepton identification and good acceptance are also important, giving the three detectors complementary capabilities.

3. Measurements of the Tau Lifetime

In the standard model, tau semileptonic decay proceeds in perfect analogy to muon decay. This leads to a simple relationship between the τ and μ lifetimes:

$$\tau_\tau = \left(\frac{m_\mu}{m_\tau}\right)^5 \tau_\mu \, B(\tau \to e\nu_\tau\bar{\nu}_e) \quad .$$

That is, if the tau couples to the charged weak bosons with the same strength as the muon, and if the interaction is $V - A$, and if the tau neutrino is massless, the tau lifetime is predicted to be $\tau_\tau = (2.82 \pm 0.18) \times 10^{-13}$ s. The theoretical uncertainty arises because of the present experimental uncertainty[4] in the tau semileptonic branching ratio, B.

These assumptions are few enough, and fundamental enough, that the failure of this prediction would have important consequences. For example, if the measured lifetime were greater than this prediction, a massive tau neutrino, or mixing to a heavier lepton generation, or even the failure of universality could be indicated.

The MAC and MARK II experiments have both reported new tau lifetime measurements. The MAC collaboration at PEP has determined the tau lifetime by measuring the mean impact parameter of tracks from tau decays. Although the impact parameter resolution is modest ($\bar{\sigma}_\delta \approx 900\ \mu$) and the expected effect small ($\delta \approx 50\ \mu$), the huge statistic available (23,000 tracks!) gives considerable precision. They find the mean impact parameter to be $46.7 \pm 5.1\ \mu$. The corresponding tau lifetime is $(3.3 \pm 0.4 \pm 0.4) \times 10^{-13}$ s, where a Monte Carlo simulation is used to relate impact parameter and lifetime. The data is shown in Fig. 1. The slight offset in the mean is visible as the small but distinct asymmetry in the height of bins at positive and negative impact parameter. That the systematic uncertainty is only 1% of the typical measurement accuracy is a remarkable testament to the cancellation of systematic effects in impact parameter measurements.

The MARK II collaboration has improved significantly on the early tau lifetime measurements[5] by employing its high precision drift chamber. The improved tracking accuracy effectively eliminates measurement bias and greatly enhances the statistical power of their data sample. They use the now familiar technique of measuring the decay length by determining the distance between the known collision point and the three particle vertex resulting from $\tau \rightarrow \nu 3\pi$ decays. Figure 2 shows the decay length distribution measured by the MARK II detector. The full PEP data set, an integrated luminosity of 209 pb^{-1} at $\sqrt{s} = 29$ GeV, has been used in the measurement, giving 807 decays including the 156 previously published.[6] The average decay length resolution is $1000\ \mu$, comparable to the mean decay length $\bar{l} = 635 \pm 36\ \mu$. The lifetime is determined by a maximum likelihood fit to two parameters, the average decay length and a factor which scales the estimated resolution. The result is $\tau_\tau = (2.86 \pm 0.16 \pm 0.25) \times 10^{-23}$ s.

A summary of these and other tau lifetime measurements is given in Fig. 3. The experiments are in good agreement with each other and in excellent agreement with the theoretical prediction. The most recent result from MARK II confirms $\mu - \tau$ universality to the level of 5% , to be compared to $\mu - e$

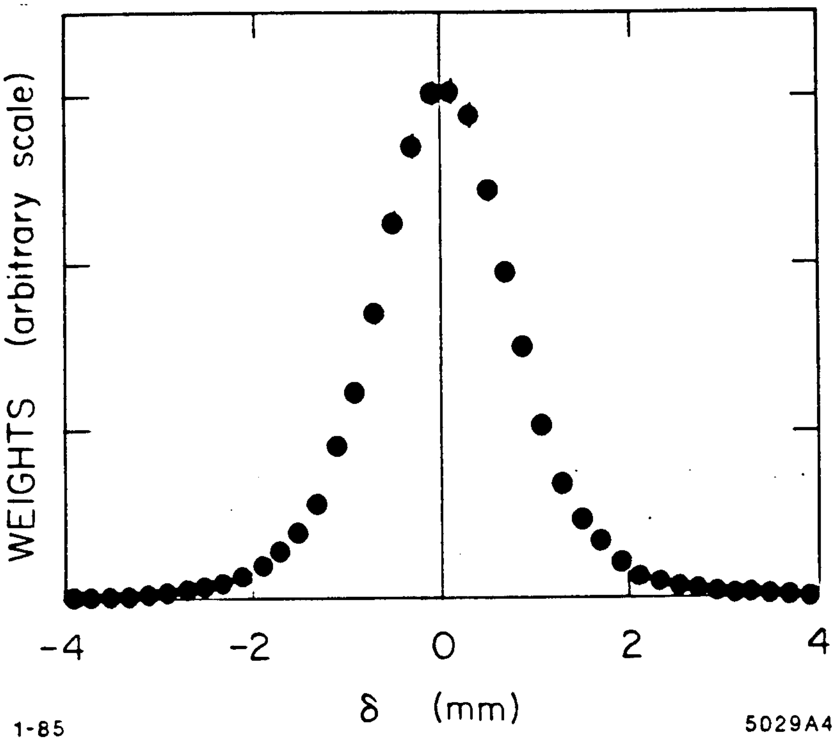

Fig. 1. Impact parameter distribution of tracks from tau decays from the MAC collaboration at PEP.

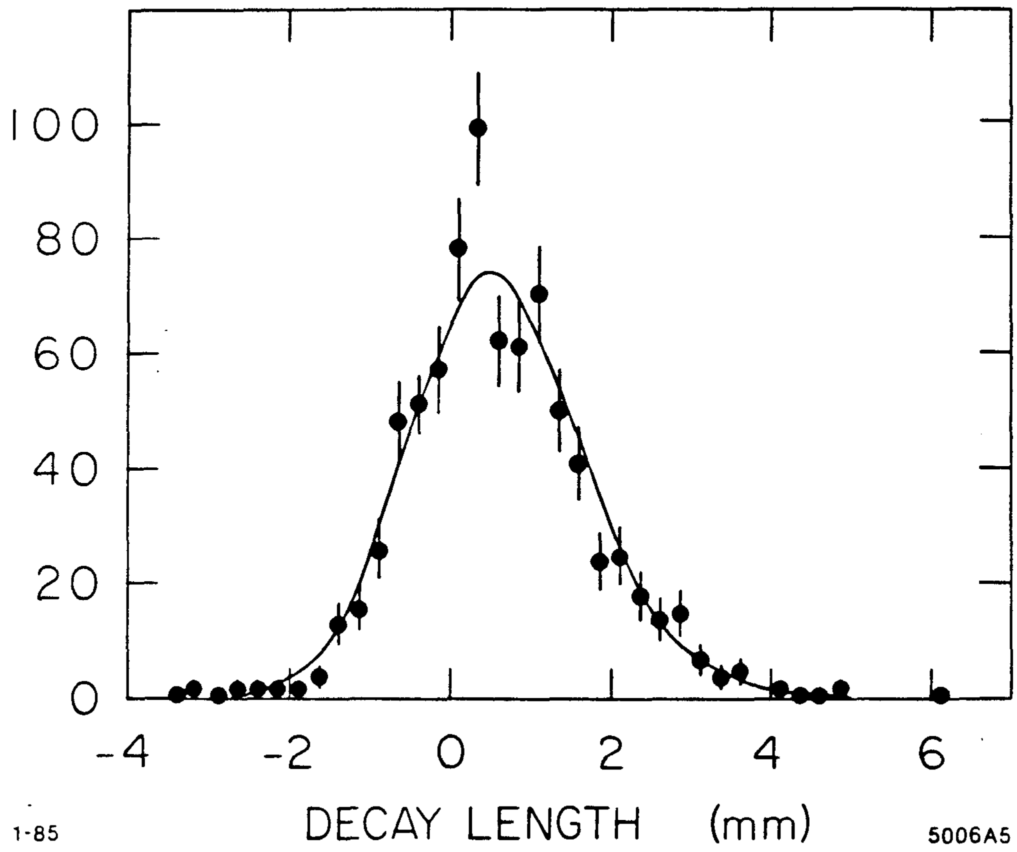

Fig. 2. Tau decay lengths measured by the MARK II collaboration at $\sqrt{s} = 29$ GeV at PEP.

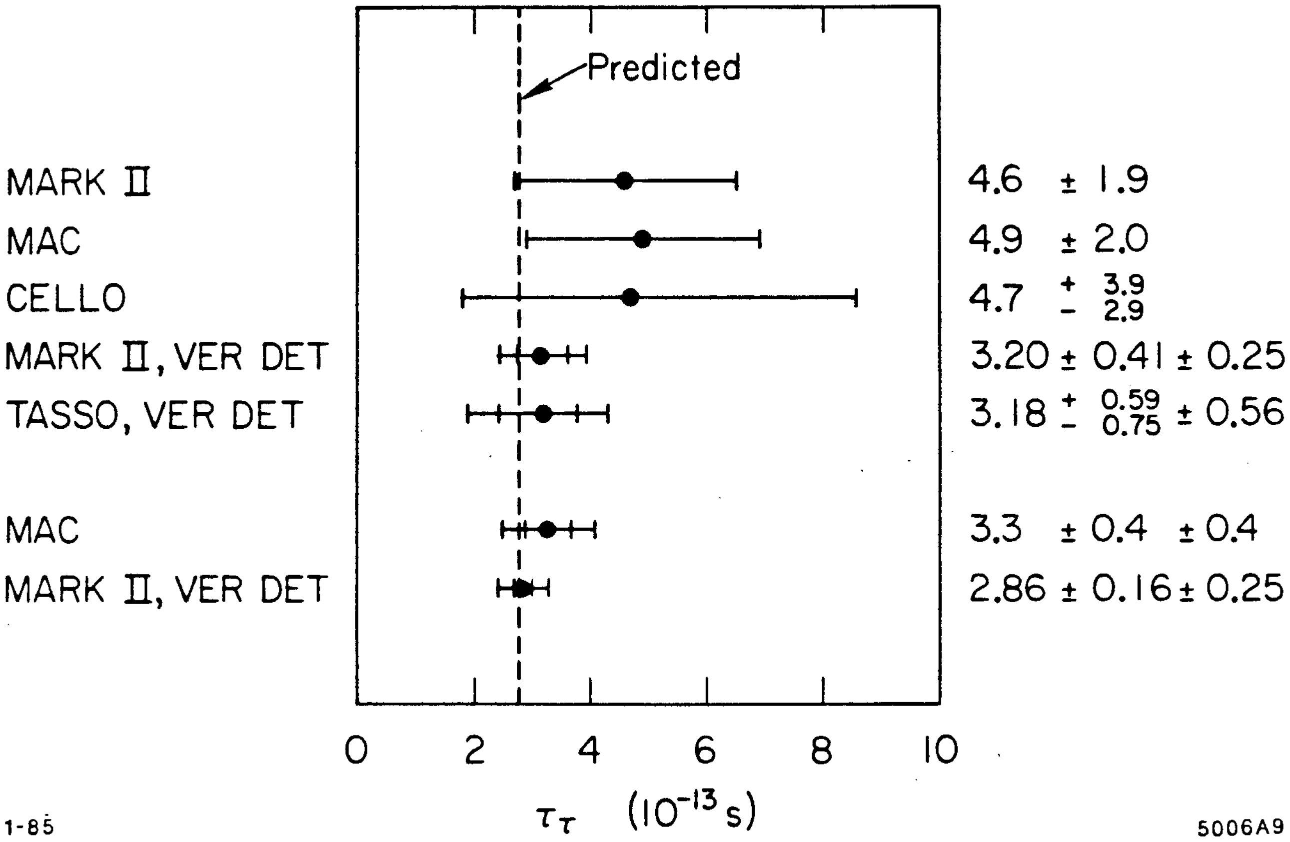

Fig. 3. Tau lifetime measurements. Data from Refs. 5 and 6.

universality which is known from studies[7] of pion decay to the 0.8% level.

The data can be used to place limits on the tau neutrino mass and mixing effects in the lepton sector if we assume universality is valid. The tau neutrino mass is constrained to be less than 322 MeV/c^2 at 95% C.L., which is not competitive with limits derived from other measurements.[8] If the tau neutrino mixed with a neutrino heavier than the tau, the decay rate would be suppressed by a factor $\cos^2\theta$, where θ is the mixing angle. The present data cannot exclude the possibility of rather large mixing effects: at 95% C.L., $\sin\theta < 0.46$.

High precision tests of $\mu - \tau$ universality will require not only increasingly accurate measurements of the τ lifetime, but similar improvements in measurements of the tau semileptonic branching ratio and the tau neutrino mass. Uncertainties in the predicted lifetime coming from these factors are at the 5% level at present, comparable to the statistical error of the MARK II measurement.

4. D^0 Lifetime Measurement

The MARK II Collaboration has used a similar technique to measure the D^0 lifetime.[9] The D^0 is identified in the decay chain $D^{*+} \to \pi^+ D^0$, $D^0 \to K^-\pi^+$. The distinctive decay kinematics of the D^* permit the isolation of a signal with only 7% background, when the D^* has at least 60% of the beam energy. The distance between the $K\pi$ decay vertex and the beam position gives the decay length. From this and the measured D^0 momentum the proper lifetime can be found. The data all comes from PEP running at $\sqrt{s} = 29$ GeV, where a total integrated luminosity of 136 pb^{-1} was analyzed. Twenty-seven D^0 decays have been identified. Figure 4a shows the lifetime distribution for these events, which contrasts noticeably with that for a hadron control sample, shown in Fig. 4b. A maximum likelihood fit to the data gives a D^0 lifetime, $(4.2^{+1.3}_{-1.0} \pm 1.0) \times 10^{-13}$ s, which is in good agreement with the current world average,[10] $(3.7^{+.5}_{-.4}) \times 10^{-13}$ s.

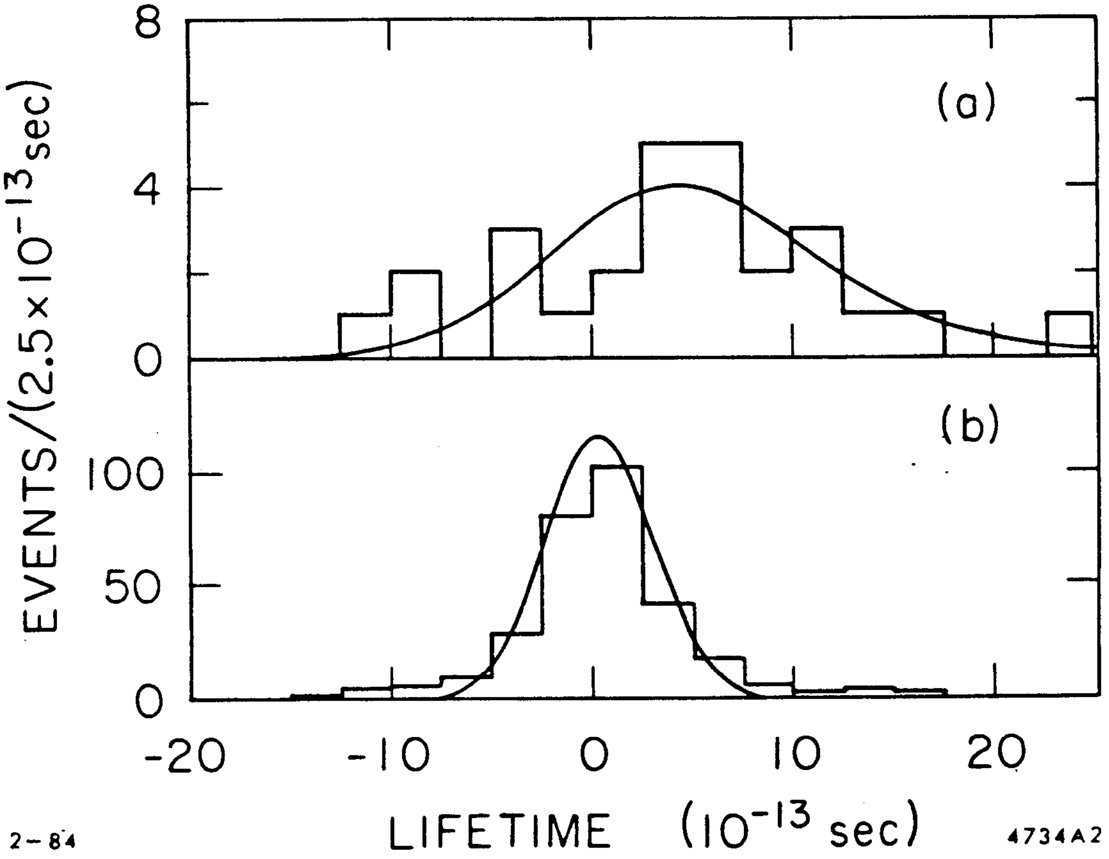

Fig. 4. (a) Measured D^0 lifetimes from MARK II; (b) Measured "lifetimes" of the hadron control sample.

5. *B* Lifetime Measurements

The B lifetime is an interesting physical quantity because it is a direct measure of the strength of the weak transitions between quark generations. In principle it depends on two of the $K-M$ matrix elements describing quark mixing, V_{bc} and V_{bu}. In practice the b quark couples predominantly to charm, so the B lifetime measures the magnitude of V_{bc}. This quantity is a fundamental parameter in the standard model and is of interest in its own right. It takes on special importance since it is the last piece of experimental information needed to deduce the magnitudes of the remaining matrix elements in the $K-M$ model.

Studies of K decay phenomenology had led to estimates[10] of the B lifetime in the 5×10^{-14} s range. The corresponding value for $|V_{bc}|$ is about .2, which is comparable to the familiar Cabibbo mixing, $|V_{su}| = .22$. So it was something of a surprise when the MAC and MARK II experiments reported[11] last year that the B lifetime is roughly 1 ps. Both the MAC and MARK II experiments have updated their results from last year with additional data and some refinements to their analyses. Additional confirmation that the B lifetime is long has recently come from the DELCO experiment. All three analyses are discussed below.

All three experiments measure the B lifetime using essentially the same technique. The reaction $e^+e^- \rightarrow b\bar{b}$ is tagged by selecting events with a lepton which has a large momentum transverse to the thrust direction. The impact parameter of these leptons is measured and contamination by charm decays and background processes accounted for. Finally, Monte Carlo calculations are used to relate the average impact parameter to the B lifetime.

Clearly this method demands a quantitative understanding of the lepton signal, its composition, backgrounds, momentum and transverse momentum dependence. Fortunately inclusive lepton production has been well studied in high energy e^+e^- annihilation.

5.1 INCLUSIVE LEPTON PRODUCTION

Most of the PEP and PETRA experiments have measured inclusive lepton production[12] as a function of the lepton momentum and its component transverse to the jet direction (as measured by thrust or sphericity). The jet direction tracks the heavy quark direction rather well, so the transverse momentum dependence is essentially just that expected from the quark decays. The average transverse momentum of the leptons from heavy quark decays scales with the quark mass. Hence the bottom quark, with its high mass, can be distinguished from charm. As seen in Fig. 5, a cut at 1 GeV/c in lepton p_T gives a relatively clean b sample. The experiments fit the observed distributions in lepton p and p_T to the sum of three terms: leptons from semileptonic B decay, leptons from semileptonic charm decay, and "leptons" from background processes. There is good agreement among the experiments on the magnitudes of the charm and bottom contributions, and since the amount of $c\bar{c}$ and $b\bar{b}$ production is presumed known, average charm and bottom semi-leptonic branching ratios can be determined. These agree nicely with results from CESR and SPEAR, lending credibility to the whole process. Finally, the longitudinal momentum dependence of the cross-sections determines the b and c quark fragmentation functions. In sum, the lepton signal is sufficiently well understood that it can be used as a tool in the lifetime measurements.

5.2 IMPACT PARAMETRY

Each of the experiments determines a signed, projected impact parameter by measuring three quantities: 1) the lepton trajectory; 2) the B production point; and 3) the B direction. The measurement is illustrated in Fig. 6. The lepton trajectory is determined with high precision only in the (xy) plane perpendicular to the beam direction in the three PEP detectors, so the entire measurement is projected onto that plane. The B production point is a priori unknown. It is approximated by the beam center, and consequently is uncertain by the horizontal and vertical beam size which are shown as the beam envelope in the figure. As

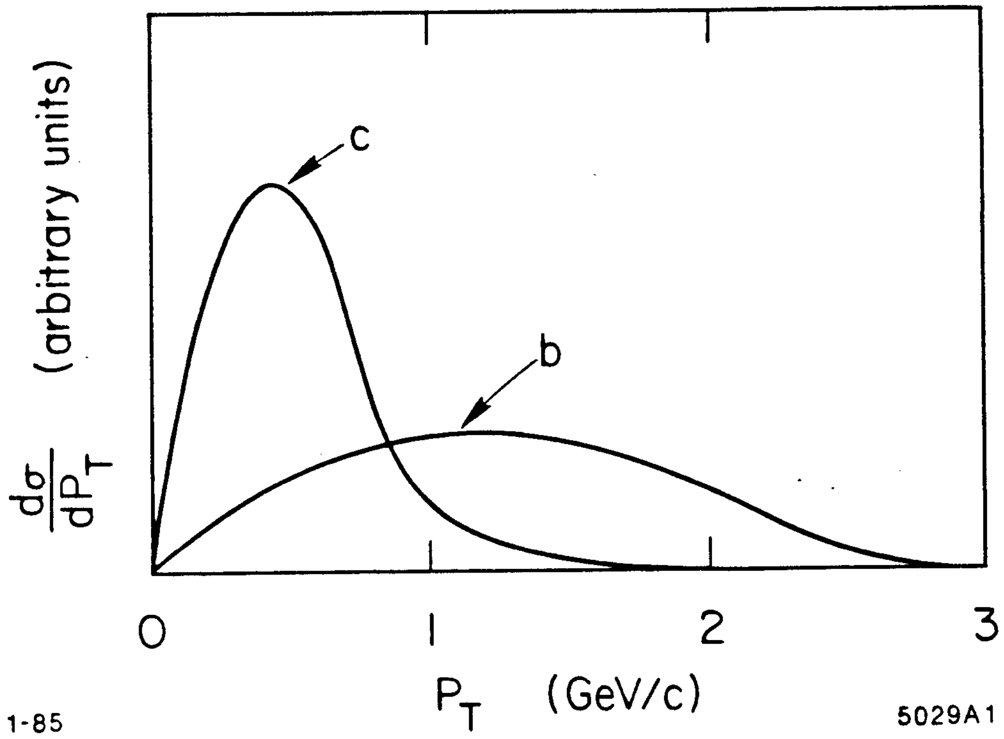

Fig. 5. Calculated transverse momentum spectrum for leptons from charm (c) and bottom (b) decays in the MARK II detector. The Monte Carlo calculation includes kinematic selection and thrust axis determination effects.

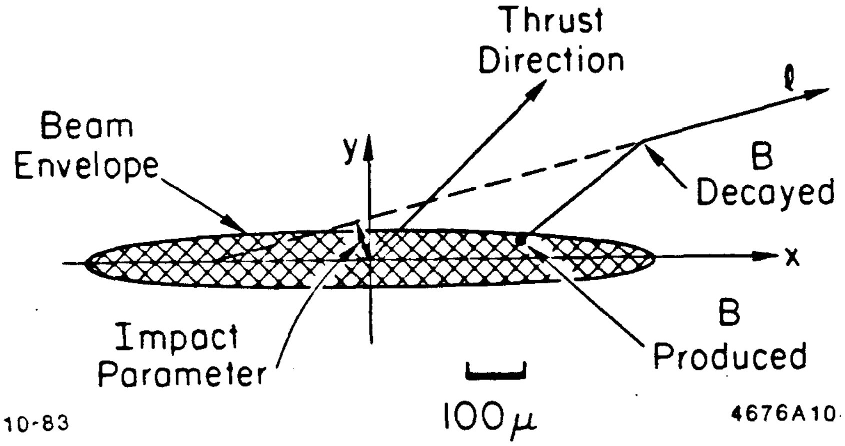

Fig. 6. Impact parameter measurement.

we said above, the B direction is nicely approximated by the thrust direction. Monte Carlo studies show the error in this estimate is about 8° in the MARK II. So one measures the projected distance of closest approach to the average beam position and signs the impact parameter positive if the intersection of the assumed B trajectory with the lepton trajectory corresponds to a positive decay length, and negative otherwise.

The impact parameter is inherently insensitive to the total energy of the B since it is proportional to the product of the B decay length (which scales as γ) and the decay angle (which scales as $1/\gamma$). However, as shown in Fig. 7, complete scaling behavior only sets in at rather high γ. At PEP energies, where $\gamma \approx 2$, the average impact parameter still has a weak dependence on the details of b quark fragmentation. In practice the ratio of average impact parameter to lifetime is known to 10% or better.

The impact parameter distribution is calculated by Monte Carlo methods. The calculations depend on well-known input parameters (the electron spectrum from B decay and the b quark fragmentation function) and the particulars of the jet axis determination, event selection cuts, and projection to the xy plane. A typical distribution is shown in Fig. 8a for 1 ps B lifetime. Such distributions scale with the parent lifetime, of course. Note that the distribution is very sharply peaked and has a long exponential tail. Negative impact parameters arise from occasional errors in assigning the B direction; these make the apparent decay length negative.

The distributions observed by the present generation of experiments are very different from this pure distribution because of resolution effects. Figure 8b shows the impact parameter distribution after convolution with the experimental resolution, which has been put at 200 μ in this example. There are two important components to this error (see Fig. 9). The first is the extrapolated track resolution, σ_t; the other is the component of the beam size perpendicular to the track direction, σ_b. Since the beam size error depends on the azimuth of the lepton

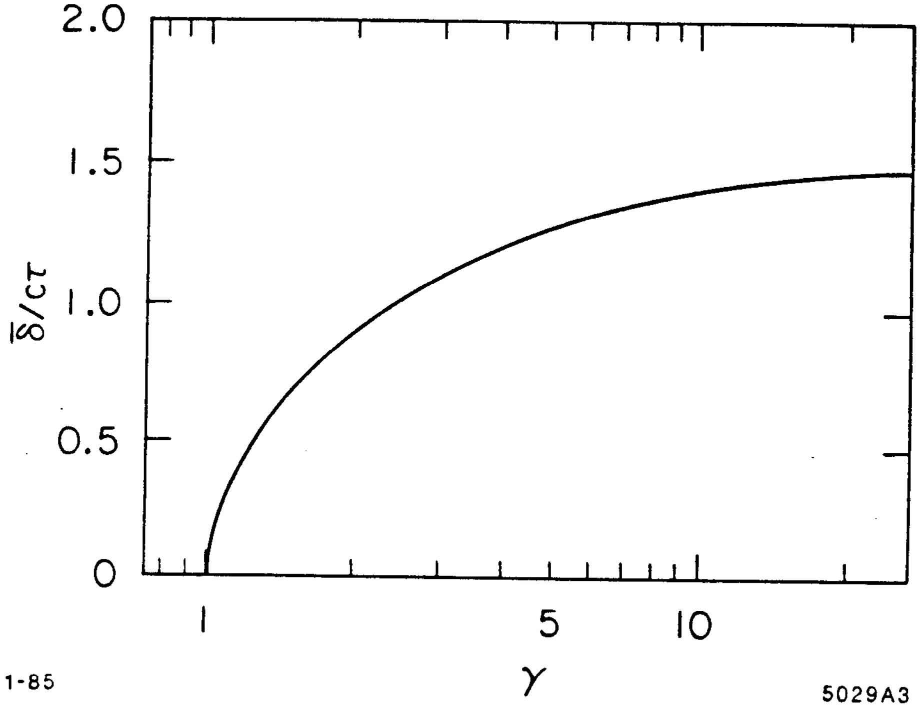

Fig. 7. Dependence of the mean impact parameter on the energy of the parent. Projection, solid angle, and kinematic selection effects have not been included.

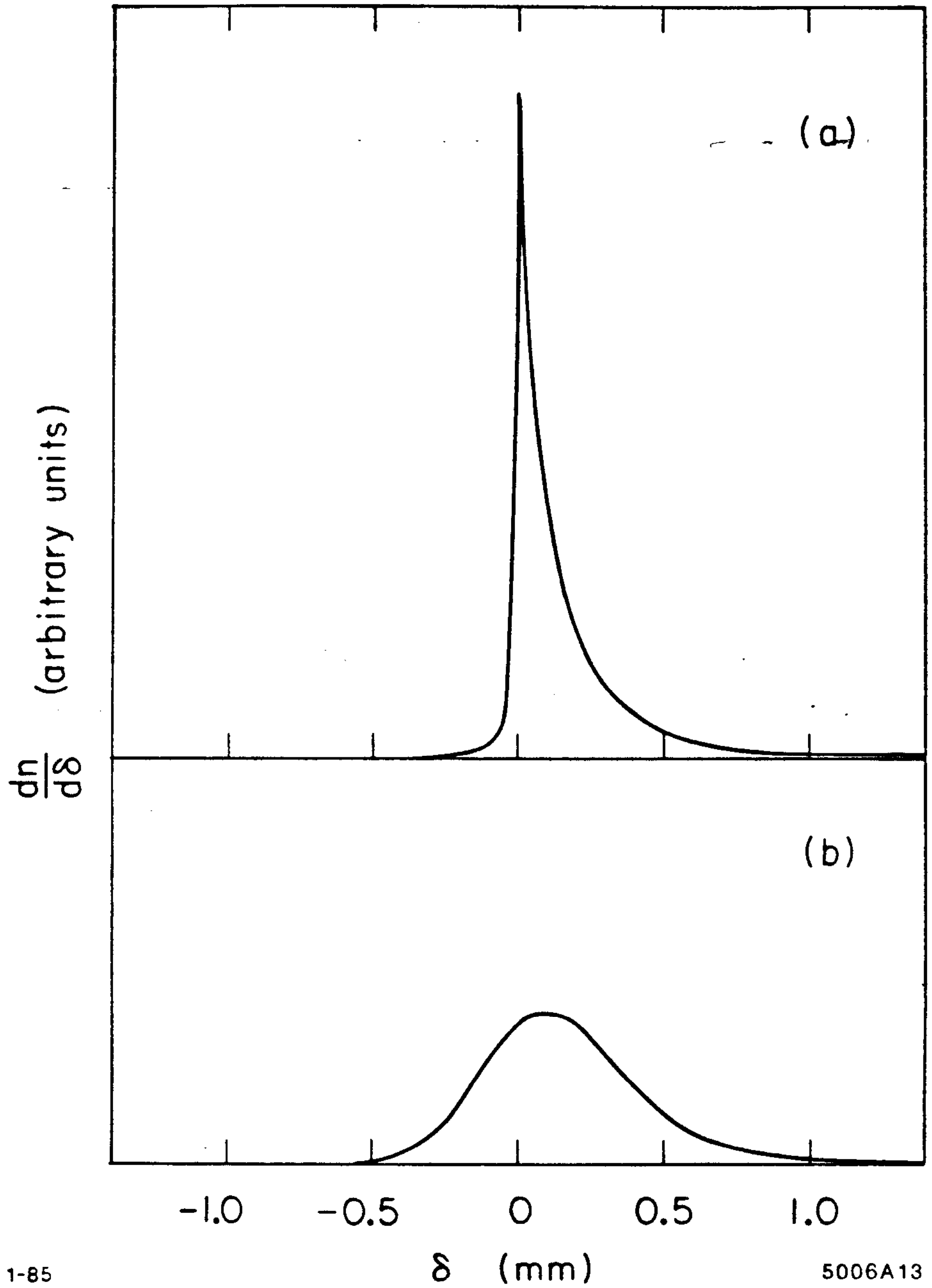

Fig. 8. Calculated lepton impact parameters for $\tau_b = 1$ ps (a) before resolution smearing; (b) after resolution smearing.

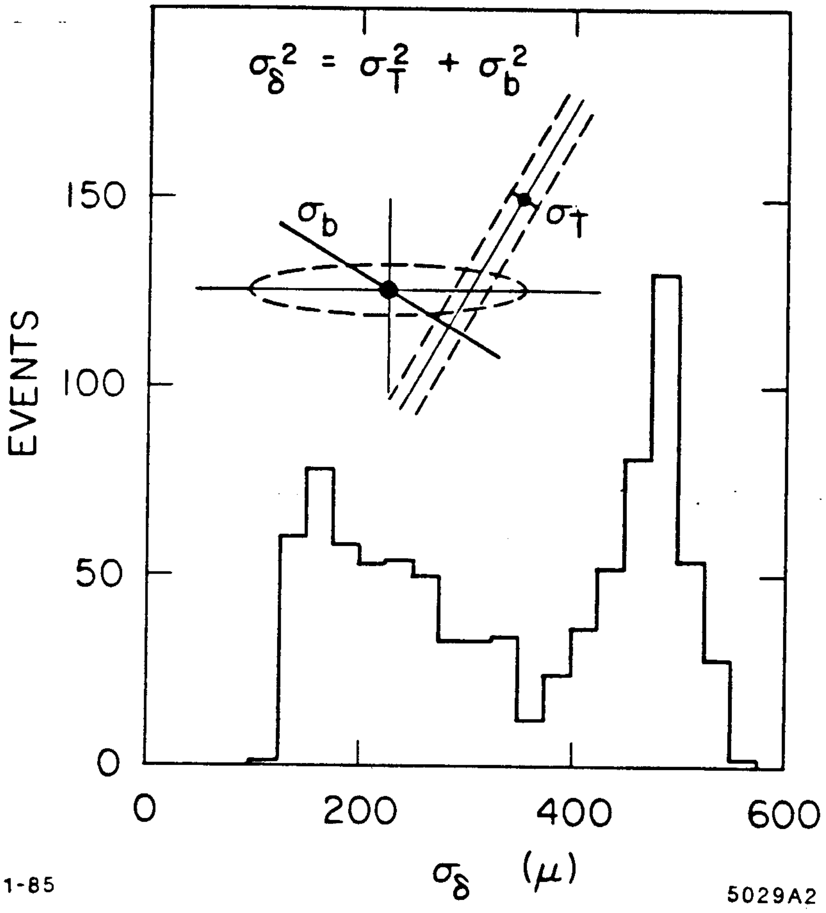

Fig. 9. Impact parameter resolution for the MARK II vertex detector.

track, there is a distribution of the overall impact parameter error, $\sigma_\delta^2 = \sigma_t^2 + \sigma_b^2$. Figure 12 shows this distribution for the MARK II measurement. It should be clear from this discussion that present experiments, which have $\langle \sigma_\delta \rangle \geq 200\ \mu$, are only sensitive to the mean of the impact parameter.

5.3 RESULTS

Some of the distinguishing features of the three experiments are shown in Table I. Different experimental techniques are used for identifying leptons and slightly different kinematic ranges are used to select $b\bar{b}$ candidates. Note in particular that the very clean lepton identification of the DELCO experiment results in a very clean $b\bar{b}$ sample that includes leptons with momenta as low as 1 GeV/c. These low momentum leptons come off at large angles and have the largest possible impact parameters, so the sensitivity of the experiment (i.e., the expected impact parameter per lifetime) is enhanced. The MAC experiment has the largest lepton sample, with nearly 400 events analyzed. The MARK II with its vertex detector has the best impact parameter resolution and, with nearly three times the data reported one year ago, the best statistical precision of the three experiments.

The impact parameter distributions from the experiments are shown in Figs. 10-12. All the experiments see mean impact parameters which are significantly positive. The observed distribution can be considered to be the sum of background, charm, and bottom components, appropriately normalized. That is,

$$\frac{dn}{d\delta} = f_{bkg} \left(\frac{dn}{d\sigma}\right)_{bkg} + f_c \left(\frac{dn}{d\delta}\right)_c + f_b \left(\frac{dn}{d\delta}\right)_b \quad ,$$

where the fractions are determined in studies of inclusive lepton production. The MAC group determines the medians of the lepton, background, and charm distributions and solves for the median of the b distribution. The DELCO and MARK II groups fit their data using maximum likelihood techniques. The background

TABLE I

	MAC	MARK II	DELCO
Lepton ID e	Pb/Gas Calorimeter	Pb/L Argon Calorimeter	Čerenkov + Pb/Scintillator
μ	Magnetized Fe Absorber	Fe Absorber	
B Enriched Region (GeV/c)	$P > 2$ $P_T > 1.5$	$P > 2$ $P_T > 1$	$P_T > 1$
$\int \mathcal{L}dt(pb^{-1})$	160	220	118
No. Leptons	398	270	60
Fraction of Lepton Candidates from B Decays	0.53	0.64	0.77
Expected Impact Parameter per Lifetime $(\delta/c\tau)$	.45	.48	.64
Average Resolution (μ)	600	200	400
Average Impact Parameter (μ)	159 ± 30 μ 83 ± 42 e	80 ± 17	215 ± 82

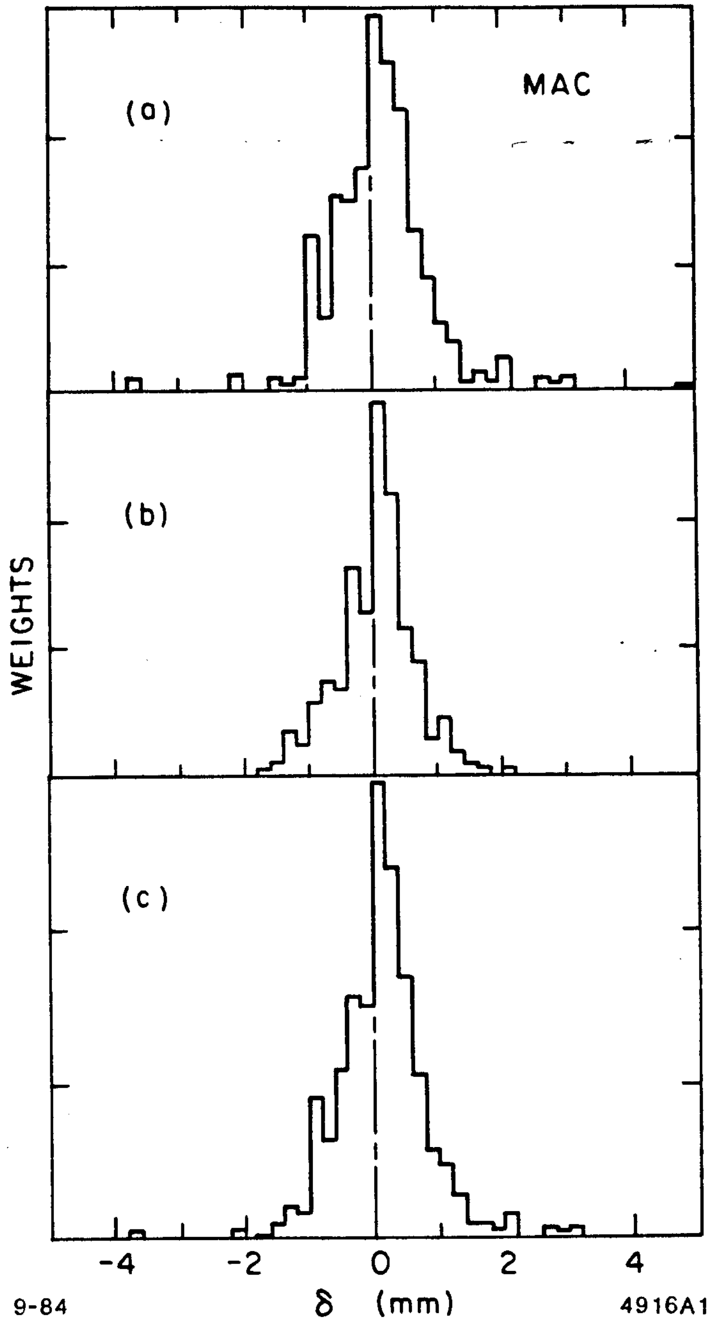

Fig. 10. Weighted impact parameter distributions from MAC. (a) muons; (b) electrons; (c) combined electrons and muons.

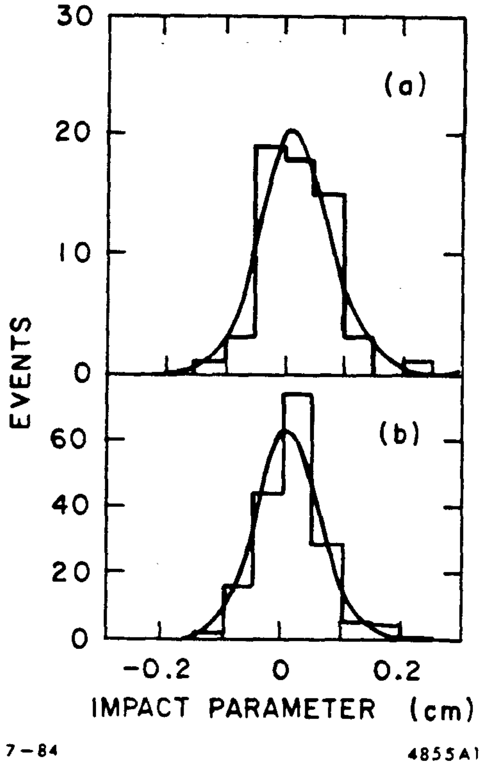

Fig. 11. Electron impact parameter distributions from DELCO. (a) *b*–region; (b) *c*–region.

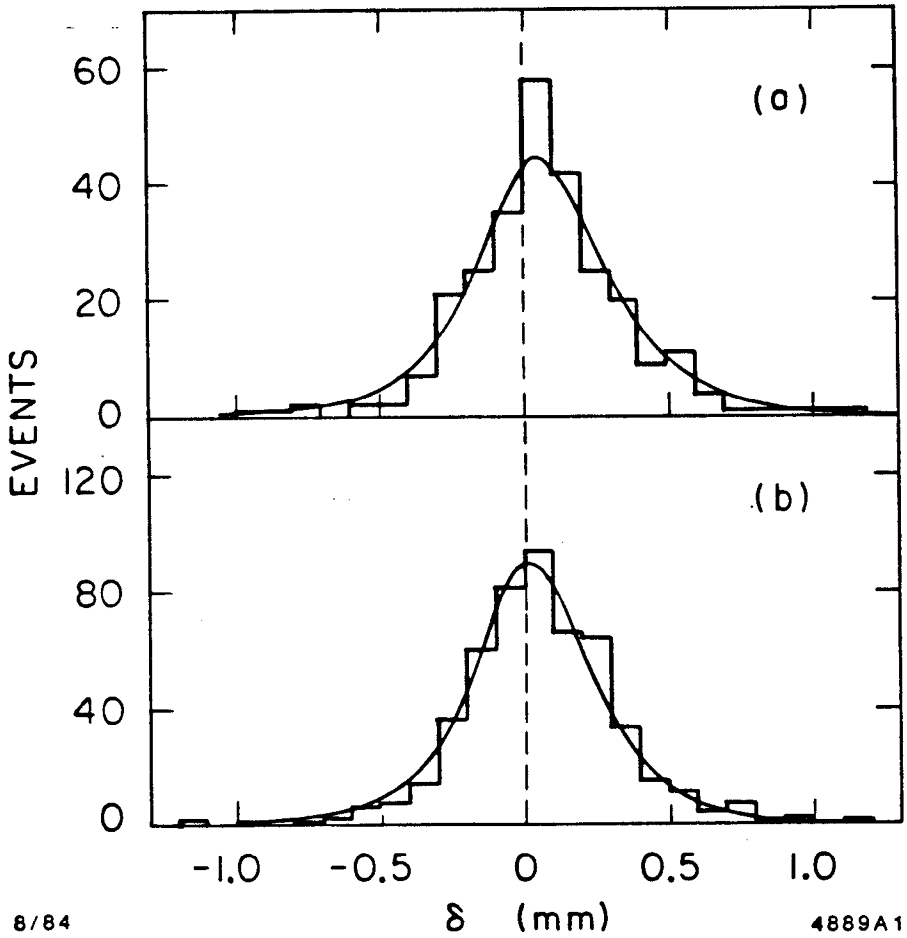

Fig. 12. Lepton impact parameter distributions from MARK II. (a) *b*–region; (b) *c*–region.

distributions are measured directly in the data. The charm distribution and the fitting function for the b distribution (as a function of lifetime) are determined with Monte Carlo methods as described above. The resulting B lifetimes are tabulated in Fig. 13. They range from the MARK II value of .85 ps to the MAC value 1.6 ps, but are certainly consistent within the large statistical and systematic errors.

Several checks have been performed in each of the experiments. The MAC and MARK II experiments find agreement between their muon and electron samples. The MARK II and DELCO experiments measure the impact parameter distribution of low transverse momentum leptons and extract average charm particle lifetimes consistent with expectation. All the experiments have measured the average impact parameter for high transverse momentum hadron tracks, and find results consistent with expectations of the Monte Carlo. Finally, all the experiments have measured the tau lepton lifetime using impact parameter techniques and find good agreement with published results.

5.4 CONCLUSIONS

The new DELCO results,[13] and the updated MAC and MARK II analyses have all confirmed that the B lifetime is in the 1 ps range. The JADE and TASSO experiments[14] at PETRA have reached similar conclusions. All of the experiments to date must use rather elaborate methods to arrive at their answers, and all pay the toll of large systematic errors. More accurate determinations of the lifetime await improved methods as well as improved tracking resolution and higher statistics.

The weighted average of the results is $1.2 \pm .2$ ps. The corresponding value for the $K-M$ matrix element $|V_{bc}|$, using a relation proposed by Lee-Franzini[15] is $|V_{bc}| = 0.047 \pm .005$. With this added input, and the row and column unitarity constraints, the magnitudes of all the $K-M$ matrix elements are determined or severely constrained. The smallness of $|V_{bc}|$ imposes interesting constraints on the

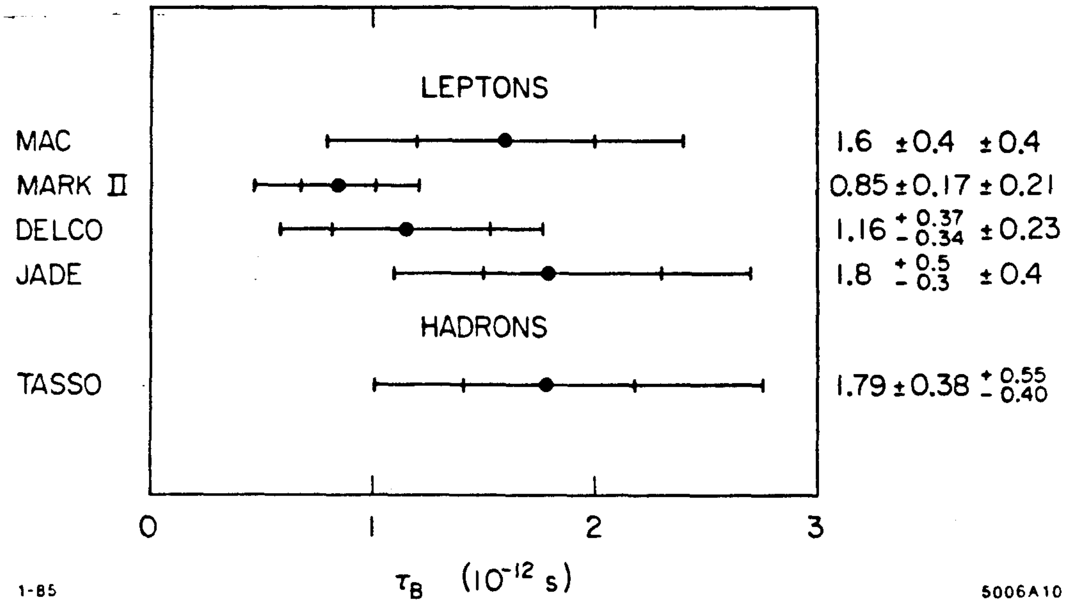

Fig. 13. Measured lifetimes of B hadrons. Additional data from Ref. 14.

top quark mass,[16] the ratio of ϵ'/ϵ in K decay,[17] and mixing and CP violation in the B system.[18] The smallness of $|V_{bc}|$ has another interesting consequence if we assume that the b quark couples to the charged weak current with the universal Fermi strength. Since its couplings to the u and c quarks are so weak, the b quark must couple predominantly to a quark more massive than itself, into which it can't decay. In other words, there must exist another charge +2/3 quark, more massive than the b quark. Thus top exists.

The long B lifetime has interesting experimental consequences too. At PEP energies the average B decay length is nearly 1 mm, so even devices with modest extrapolated track resolution ($\sim$ 100 μ) can tag long-lived B decays with practical efficiencies (few %) and low background. Figure 14 shows a very likely candidate for B decay as seen with the MARK II vertex detector. There is a clear clustering of the tracks numbered 6, 7, 8 and 14 into a vertex that is displaced about 2 mm to the left of the beam ellipse. Track 8 is identified as a muon with total momentum 2.1 GeV/c and transverse momentum 1.1 GeV/c. The invariant mass of the four prongs is 4.25 GeV/c^2. Note that the decay vertex essentially lies on the thrust axis, which is shown by the dashed line in the figure. The other tracks group in the vicinity of the beam ellipse, or perhaps a bit to its right. Tracks shown as dotted lines have not been fitted reliably. Track 13, which appears to miss both vertices, is in fact a low momentum track with a large multiple scattering error. The typical track errors on the higher momentum tracks are in the 100 μ to 200 μ range. Long live the B!

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I would like to thank Bill Ford (MAC) and Dan Klem (DELCO) for discussions of their B lifetime results.

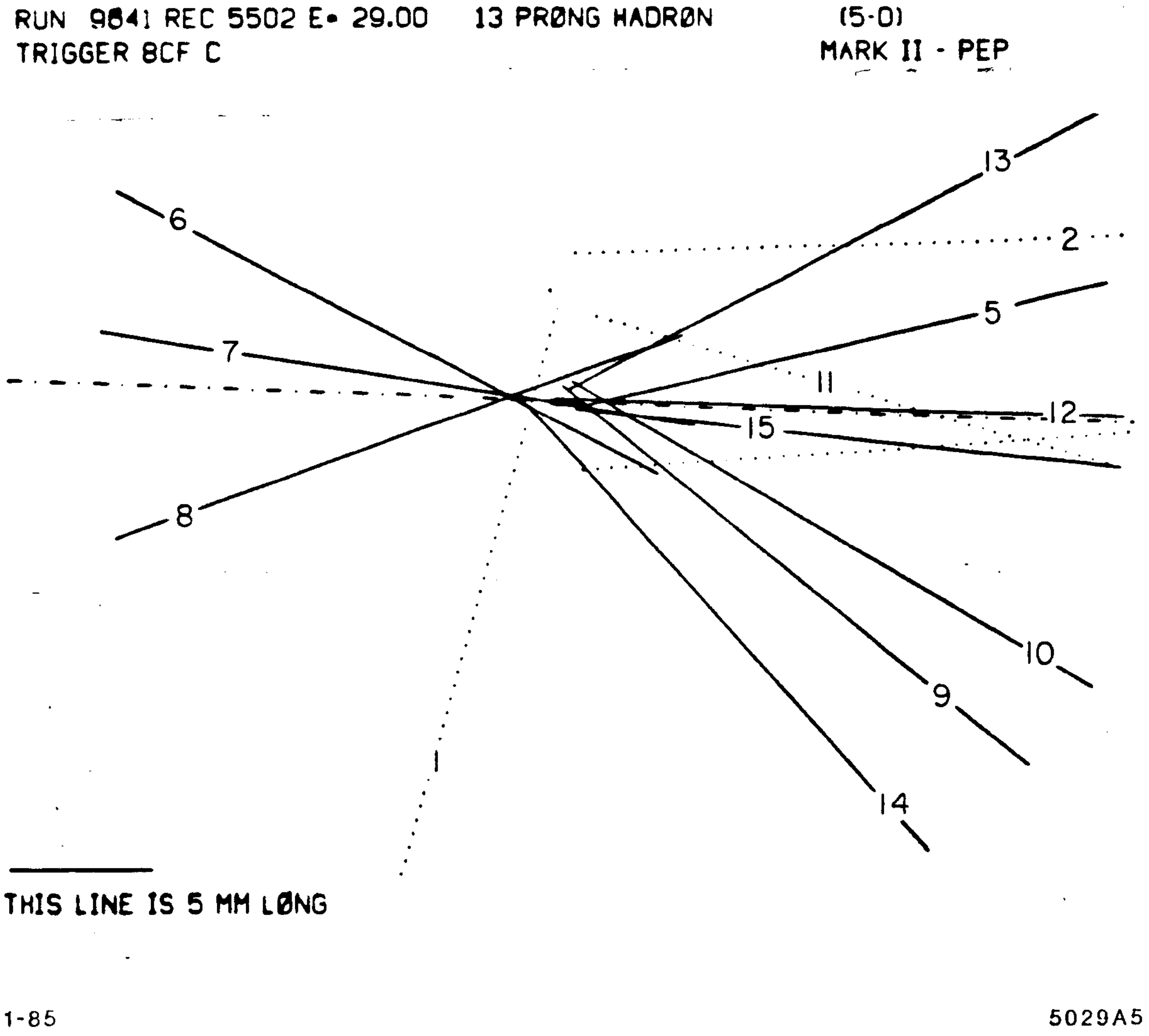

Fig. 14. A long-lived *B* decay reconstructed by the MARK II vertex detector.

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$$|V_{bc}|^2 = \frac{(2.777 \pm 0.179) \times 10^{-15}\ s}{(1 + R_b)\tau_b} \ .$$

Here we put $R_B = .03$.

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