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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, $\tau \to \nu_\tau W$ and $b \to cW$. 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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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 $\tau \to \nu 3\pi$ 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 μ, 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 $\mu - e$

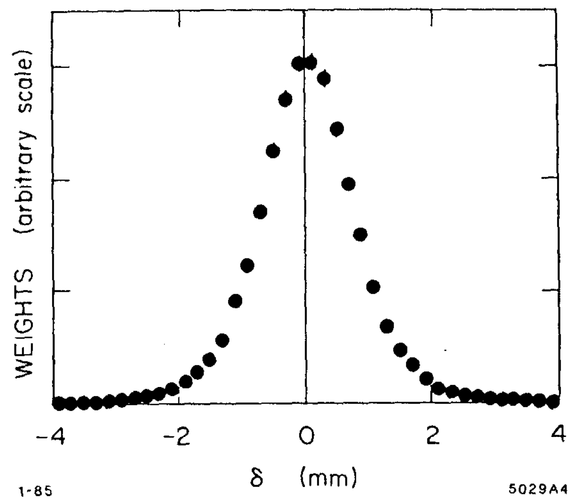

Fig. 1. Impact parameter distribution of tracks from tau decays from the MAC collaboration at PEP.

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.

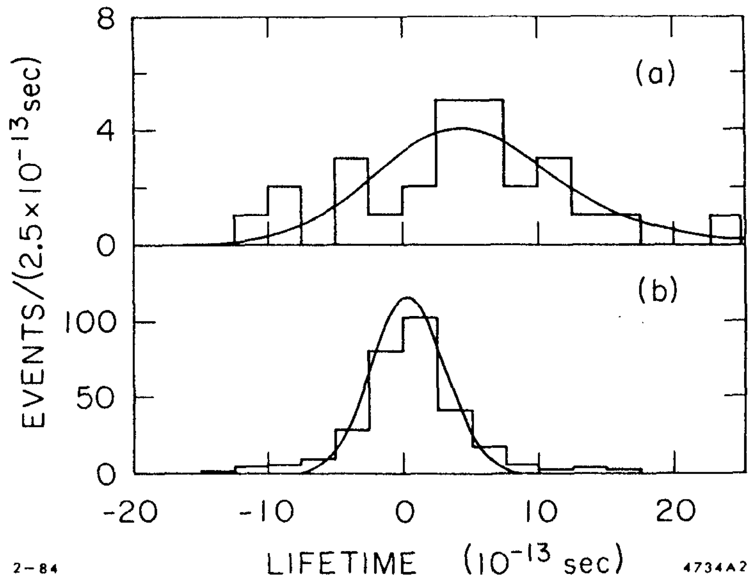

Fig. 4. (a) Measured D^0 lifetimes from MARK II; (b) Measured "lifetimes" of the hadron control sample.

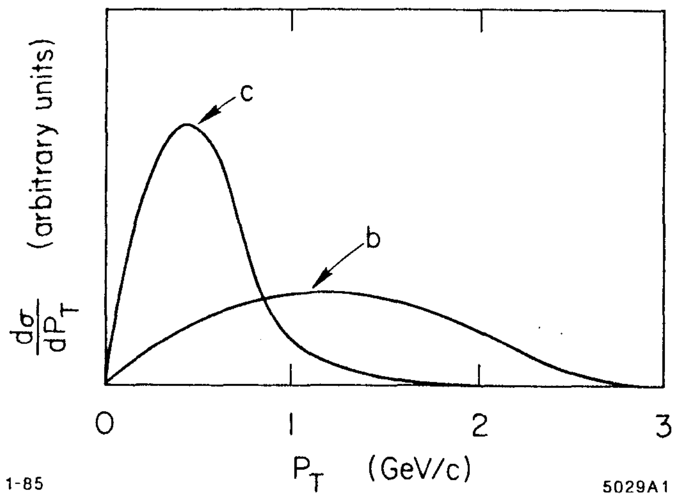

Fig. 5. Calculated transverse momentum spectrum for leptons from charm (c) and bottom (b) decays in the MARK II detector. The Monte Carlo calculation includes kinematic selection and thrust axis determination effects.

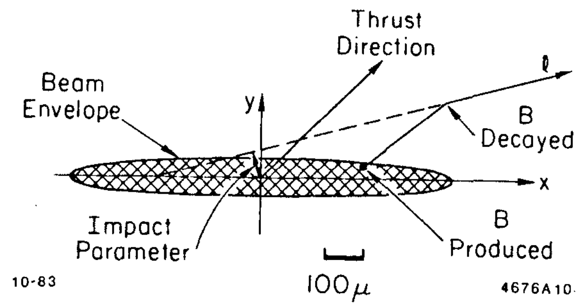

Fig. 6. Impact parameter measurement.

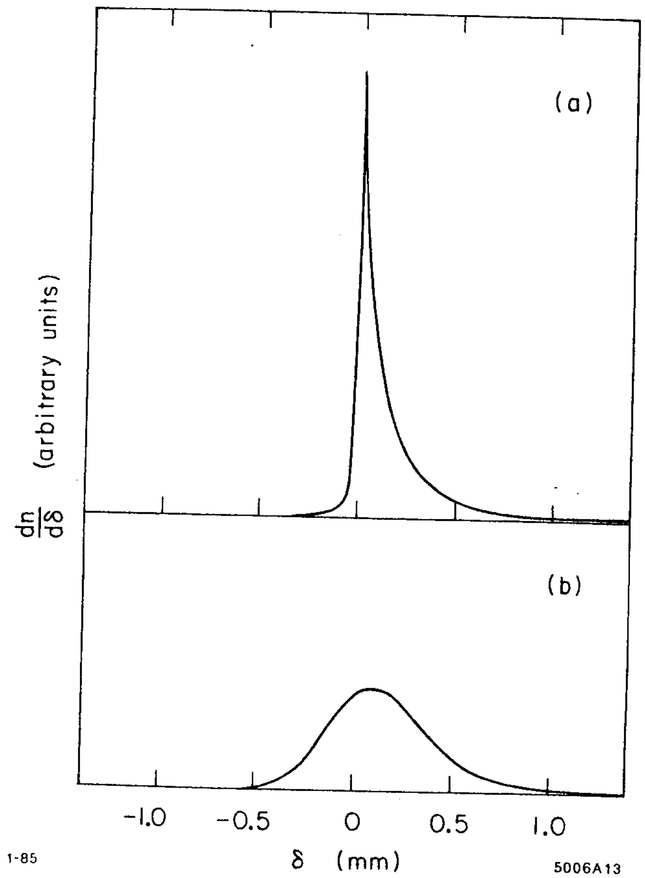

Fig. 8. Calculated lepton impact parameters for $\tau_b = 1$ ps (a) before resolution smearing; (b) after resolution smearing.

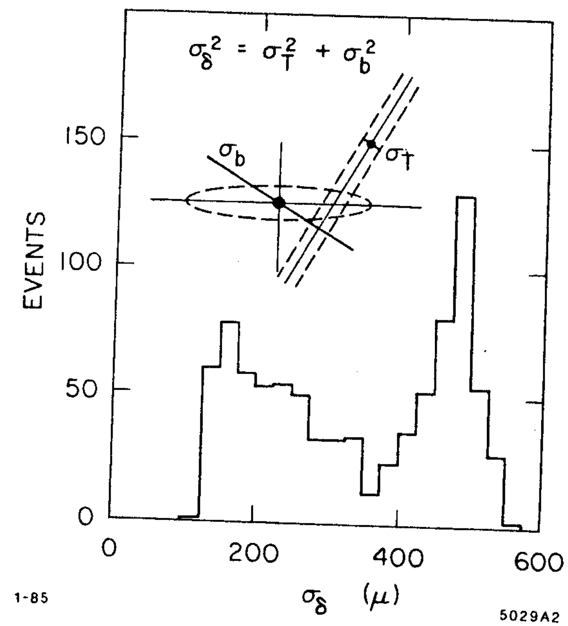

Fig. 9. Impact parameter resolution for the MARK II vertex detector.

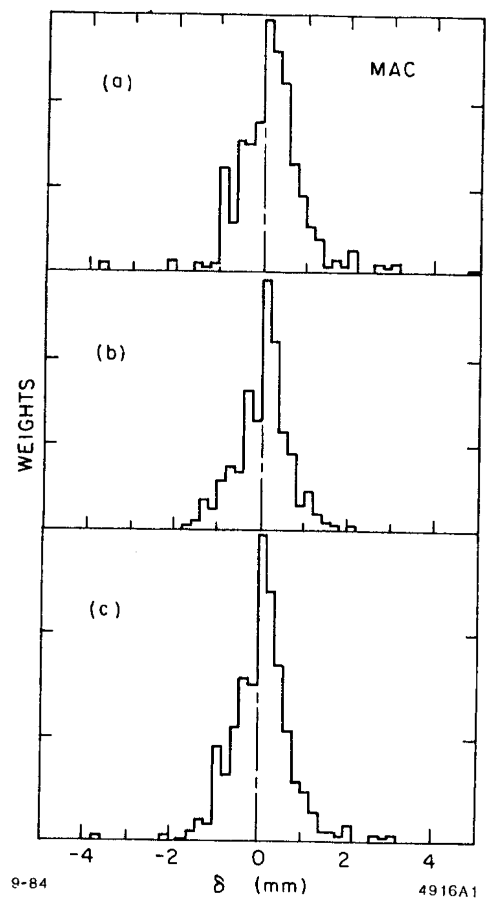

Fig. 10. Weighted impact parameter distributions from MAC: (a) muons; (b) electrons; (c) combined electrons and muons.

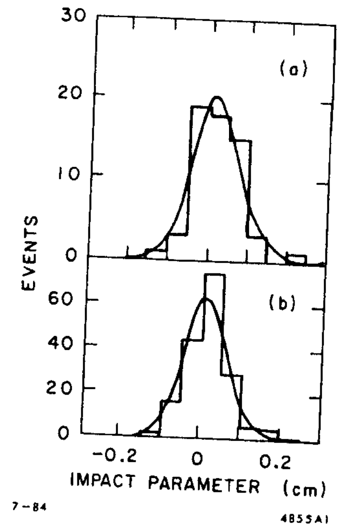

Fig. 11. Electron impact parameter distributions from DELCO: (a) b–region; (b) c–region.

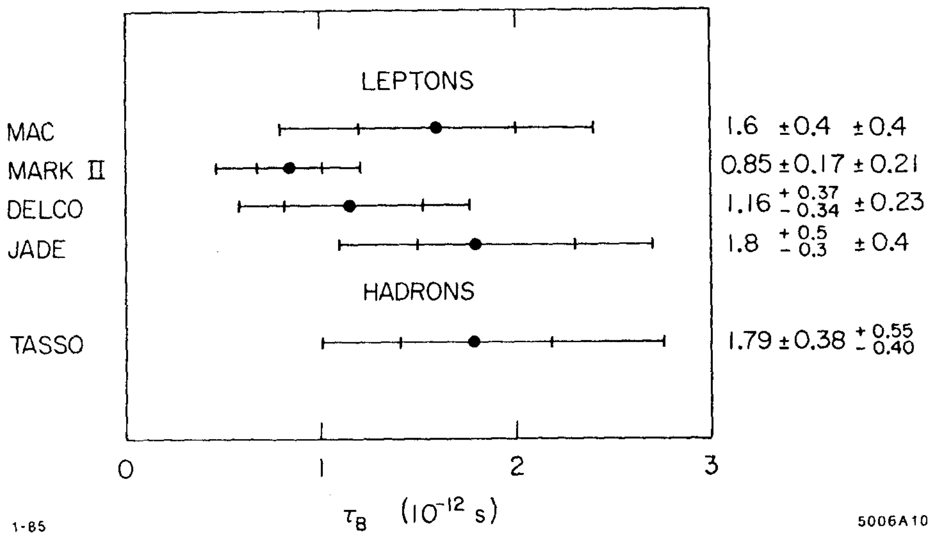

Fig. 13. Measured lifetimes of B hadrons. Additional data from Ref. 14.

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!

Acknowledgements

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Lett.; D. E. Koop *et al.*, Phys. Rev. Lett. 52, 970 (1984); M. Althoff *et al.*, DESY 84/061, (1984) submitted to Phys. Lett.

13. D. E. Klem *et al.*, Phys. Rev. Lett 53, 1873 (1984).
14. R. Klanner in *Proceedings of the International Conference on High Energy Physics, 22nd*, Leipzig, DDR, July 19-25, 1984, Zeuth, DDR, Akademie der Wissenschaften der DDR.
15. J. Lee-Franzini, Stonybrook preprint 84-0537, uses constraints from B semileptonic decay to relate $|V_{bc}|$ and τ_b as follows:

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

Here we put $R_B = .03$.

16. P. Ginsparg, S. Glashow and M. Wise, Phys. Rev. Lett. 50, 1415 (1983).
17. F. Gilman and J. Hagelin, Phys. Lett. 126B, 111 (1983).
18. See for example L. L. Chau and W. Y. Keung, Phys. Rev. D29, 592 (1984).