STATUS OF THE TAU ONE PRONG PROBLEM*

KENNETH G. HAYES

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309

ABSTRACT

The present status of the tau one prong problem is reviewed. Emphasis is placed on recent published branching fraction measurements, the status and implications of tau lifetime measurements, and measurements which constrain the sum of branching fractions to be unity.

*Work supported by the Department of Energy, contract DE-AC03-76SF00515.

1. Introduction

In high energy e^+e^- interactions, events from the reaction $e^+e^- \to \tau^+\tau^-$ can be cleanly and efficiently selected by exploiting their distinct event topology. It is therefore possible to make precise measurements of the topological branching fractions to tau decay modes containing a specific number of charged particles. The current world average values for the topological branching fractions B_n $(n = 1, 3, 5, 7)$ for the decays $\tau^- \to (n\ charged\ prongs)^- + neutrals$ are listed in Table 1. Note that the precision of the world average value for B_1 is about 1 in 300.

The one charged prong topological branching fraction must be equal to the sum of branching fractions for all exclusive modes containing one charged particle, $B_1 = \sum_i B_i$. This sum includes modes which have been well measured such as $\tau^- \to e^-\bar{\nu}_e\nu_\tau$, $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$, $\tau^- \to \pi^-\nu_\tau$, and $\tau^- \to \rho^-\nu_\tau$ (with branching fractions B_e, B_μ, B_π, and B_ρ respectively), and modes that are unmeasured or very poorly measured like $\tau^- \to \pi^-(\geq 3\pi^0)\nu_\tau$ and $\tau^- \to \pi^-(\geq 1\eta)(\geq 0\pi^0)\nu_\tau$. The current status of the one prong modes is summarized in Table 2. Theoretical predictions from Ref. 2, updated to include new experimental data and electroweak radiative corrections[3], are also listed in Table 2. If the theoretical predictions are used for the unmeasured or poorly measured modes, then the difference between B_1 and the sum of exclusive one prong modes is $B_1 - \sum_i B_i > 5.6 \pm 1.8\%$. If the theoretical prediction is substituted for the experimental branching fraction for $\tau^- \to \pi^-2\pi^0\nu_\tau$ (the mode in the sum with the largest experimental error), the difference becomes $B_1 - \sum_i B_i > 6.3 \pm 1.3\%$, nearly a five sigma effect.

There are 5 possible causes of the discrepancy: an error in one or more of the experimental branching fractions B_i, an underestimate of one or more of the experimental uncertainties on the branching fractions, correlated errors between experimental measurements which are not properly taken into account by the averaging procedure, errors in the theoretical predictions, or the existence of one or more decay modes (perhaps small) which are not included in the table. A combination of several or all of these factors may contribute to the discrepancy.

The discrepancy has motivated many new measurements of tau decay properties.

Figure 1 plots by year the number of experimental publications of tau lifetime or branching fraction measurements[1]. Shortly after the discrepancy was noticed[2,4], there was a large increase in the number of published results. Experiments at PEP and PETRA contributed the bulk of these measurements, and the rate of new measurements has decreased as analysis of data from these experiments is completed.

2. Branching Fraction Measurements

In this section, a brief summary of the status of many experimental branching fraction measurements relevant to the 1 prong problem is presented. Emphasis is given to results published within the previous year.

$\underline{B_1}$: Since 1985, the HRS collaboration's measurement of B_1 (Ref. 5) has been the most precise, accounting for about half of the weight in the world average[6]. The collaboration has recently updated their result to include the full PEP data sample. These two measurements are listed in Table 3. The CELLO collaboration has published the second most precise measurement of B_1 which is also listed (along with earlier CELLO measurements) in Table 3. All published measurements of B_1 are shown Figure 2. Most of the early low center of mass energy measurements are systematically lower than the precise high energy measurements. The average of the 9 independent PEP/PETRA measurements listed in Table 4 is $86.0 \pm 0.3\%$ and has a χ^2 of 13.1 for 8 degrees of freedom. Assuming Gaussian errors, the probability of observing a larger χ^2 is 11%. Figure 3 shows the Particle Data Group averages for B_1 from 1978 to 1988 along with the current world average. The new CELLO and HRS results lower the 1988 world average of $86.6 \pm 0.3\%$ by 0.6%. Although this is a 2 standard deviation change, it reduces the 1 prong deficit by only about 10%. If an error in B_1 is the major source of the 1 prong deficit, then it is a very significant error indeed!

$\underline{B_e,\ B_\mu}$: The Mark J collaboration has recently published[12] an updated value for B_μ of $17.4 \pm 1.0\%$ based on 2197 events, about twice the statistics of their 1986 measurement[13] ($17.4 \pm 0.6 \pm 0.8\%$). The improved statistical error of the new measurement has been offset by an expanded estimate of the systematic errors, resulting in the same total error (statistical and systematic errors added in quadrature). Systematic errors dominate this measurement with uncertainty in the integrated luminosity making the largest contribution. No other recent measurements have been published.

There are 21 published measurements of B_e and/or B_μ which are from statistically independent experiments. Since some measurements make use of the constraint on B_e and B_μ provided by $\mu - e$ universality ($B_\mu = .973 B_e$), a useful method to compare and average the various results is to apply the universality constraint to all measurements (see Ref. 6). Figure 4 shows the constrained electron branching fraction B_e' for all published measurements. Unlike the B_1 measurements, all B_e' measurements are consistent with the current world average ($\bar{B}_e = 17.96 \pm 0.26\%$). This is also consistent with the early theoretical predictions for B_e (see section 5).

<u>B_ρ:</u> The Argus collaboration has published[14] the first measurement of B_ρ from either CESR or DORIS ($21.5 \pm 0.4 \pm 1.9\%$) from a data sample containing 202,000 produced tau pairs. The measurement is dominated by systematic errors; the three largest are from uncertainties in acceptance (1.7%), luminosity (0.9%), and backgrounds (0.4%).

All experimental measurements[14,15] of B_ρ are plotted in Fig. 5. The Mark II collaboration has published two measurements from the same data set but using different analysis techniques. Although both are shown in Fig. 5, only the measurement with smallest errors is used in the world average with the other seven measurements yielding $\bar{B}_\rho = 22.3 \pm 0.8\%$.

<u>B_π:</u> There are no recent measurements of B_π. The current world average of all published measurements[15] (shown in Fig. 6) is $\bar{B}_\pi = 10.8 \pm 0.6\%$.

<u>Other measurements:</u> There have been several other recent measurements of modes listed in Table 1. Using its large tau sample, the Argus collaboration has published[14] the most precise measurement for the decay $\tau \to K^*(892)\nu_\tau$ of $B_{K^*(892)} = 1.23 \pm 0.21^{+0.11}_{-0.21}\%$. The collaboration has also published several limits[16] on modes containing η's including the most stringent limit on inclusive η production in tau decay: $B(\tau^- \to \eta X^- \nu_\tau) < 1.3\%$ at 95% confidence level. It is extremely unlikely that decays containing η's are a major source of the one prong discrepancy.

3. Experimental Systematic Errors

Many experimental measurements of tau branching fractions are now dominated by systematic uncertainties, the most significant example being the ARGUS B_ρ measurement discussed above. This section discusses the impact of systematic uncertainties on the one prong problem. These results are from a study by Martin Perl and myself which is described in more detail in Ref. 6.

To form world averages of branching fraction measurements, the statistical error $\sigma_{stat,i}$ and systematic error $\sigma_{sys,i}$ of each experiment are added in quadrature, $\sigma_i^2 = \sigma_{stat,i}^2 + \sigma_{sys,i}^2$. The weighted average $\bar{B}$ and error on the average σ are calculated using

$$\bar{B} = \sum_i B_i \cdot \sigma_i^{-2} \Big/ \sum_i \sigma_i^{-2} \quad , \quad \sigma = \left[\sum_i \sigma_i^{-2} \right]^{-\frac{1}{2}} \quad .$$

The relative importance of statistical and systematic errors in the average can be examined by forming the error on the average using just the statistical errors, $\sigma_{stat} = [\sum_i \sigma_{stat,i}^{-2}]^{-\frac{1}{2}}$, and defining the systematic contribution to the error to be $\sigma_{sys} = [\sigma^2 - \sigma_{stat}^2]^{\frac{1}{2}}$. Note that σ_{sys} is not equal to $[\sum_i \sigma_{sys,i}^{-2}]^{-\frac{1}{2}}$. The ratio of systematic to statistical errors in the world average for B'_e, B_ρ, and B_π is 1.0, 2.5, and 2.1 respectively. Note that for these modes, which make up the bulk of the one prong branching fraction ($1.973 * B'_e + B_\rho + B_\pi = 68.5 \pm 1.12\%$), the world averages are dominated by systematic uncertainties.

The averaging procedure does not have a rigorous statistical foundation when the individual experimental measurements are dominated by systematic uncertainties, since many can only be roughly estimated by the experimenter and/or have a distribution which is unknown or only approximately Gaussian. The significance of the discrepancy, $B_1 - \sum_i B_i > 6.3 \pm 1.3\%$ (if theoretical values are used for $B_{\pi^- 2\pi^0}$), should not be evaluated assuming the error distribution is Gaussian.

By looking at the scatter of the individual measurements about their average value, the consistency of the individual error assignments can be tested. Figure 7 shows the distribution of residuals, defined as $z_i = (B_i - \bar{B})/[\sigma_i^2 - \sigma^2]^{\frac{1}{2}}$. For accurate experiments having correctly specified Gaussian errors, the residual distribution is a normal distribution of unit width and zero mean. It is apparent from the Fig. 7 that the measurements are overconsistent; some experimental errors have been overestimated and/or some measurements are biased towards the mean. By studying the residual distribution when only statistical errors are used, there is clear evidence for bias in the B_ρ measurements and weak evidence for bias in the others.

Although there are some problems in the experimental branching fraction measurements, I know of no reason to suspect that any particular current world average value is incorrect. We are thus forced to look elsewhere for clues to the one prong problem. In the following two sections we examine the tau lifetime measurements and the attempts at theoretically predicting absolute tau decay branching fractions.

4. Status and Implications of Tau Lifetime Measurements

The JADE and TASSO collaborations have recently published new measurements of the tau lifetime τ_τ. All published results[17] for τ_τ are shown in Figure 8 and listed in Table 5. The world average value is $\bar{\tau}_\tau = 3.027 \pm 0.078 \cdot 10^{-13} sec$. Assuming $\tau - \mu - e$ universality, B_e can be determined from τ_τ using[18]

$$B_e = (\tau_\tau/\tau_\mu) \cdot (m_\tau/m_\mu)^5$$

which gives $B_e = 18.92 \pm .49\%$. The difference between this prediction and the world average value for B_e is $0.96 \pm 0.56\%$, a 1.7 standard deviation effect. This hints that perhaps $\bar{B}_e$ is a bit low, although the error is too large to draw any firm conclusion. Furthermore, the relatively small error on $\bar{\tau}_\tau$ is derived primarily from the six most precise experiments which contribute about equal weight to the average. These experiments have comparable statistical and systematic errors (for $\bar{\tau}_\tau$, $\sigma_{sys}/\sigma_{stat} = 0.8$) so the small error on $\bar{\tau}_\tau$ results from assuming the systematic errors are independent and can be averaged. The total error for $\bar{\tau}_\tau$ is smaller than the systematic error on any individual experiment.

All the precise experiments employ high precision drift chambers to measure either track impact parameters from 1 or 3 prong tau decays or tau flight distances from vertex reconstruction of 3 prong decays. The measured distributions are fit using Monte Carlo simulations of the detector to calculate the expected distribution as a function of the tau lifetime. Depending on which method is used, similar systematic errors exist for each experiment.

One source of common systematic error in the lifetime measurements is the idealized vertex drift chamber model used in the Monte Carlo simulations. These detectors are often calibrated using events from the processes $e^+e^- \rightarrow e^+e^-(\gamma)$, $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$, and cosmic rays where the detected tracks are known to originate in a common vertex. These events are plentiful, simple, and each track is well isolated from other tracks in the detector as are tracks from 1 prong tau decays. However, due to the large Lorentz boost, tracks from three prong tau decays pass through the detector near to each other. The fact that these detectors project out the coordinate parallel to the beam axis increases the track density.

For several reasons, the performance of these detectors in dense track environments is worse than that for isolated tracks. For example, crosstalk can effect hit timing on nearby tracks, or can generate extra background hits not included in the Monte Carlo model. The efficiency and error rate of the pattern recognition program that assigns detected hits to tracks worsen as the track separation becomes small. The degradation of the spatial resolution from crosstalk not only directly degrades impact parameter resolution, but also further degrades the performance of the pattern recognition program. For reasons of speed and simplicity, these programs usually assume that the detector spatial resolution function is approximately gaussian, and hits from the (non-gaussian) tails of the actual resolution function may be unused, or incorrectly assigned to a nearby track. Most of the vertex detectors use single hit electronics so only the first hit on a wire is detected. Even when distinct hits for each track are detected, incorrect assignments can be made.

As examples of the effects discussed above, in the Mark II experiment, vertex detector track fit χ^2 distributions for tracks from 3 prong tau decays indicate the effective spatial resolution is 15% worse than that found in $e^+e^- \rightarrow e^+e^-$ calibration events. In the CLEO experiment, the spatial resolution in hadronic events is about 15% worse than that observed in the Bhabha calibration events. The HRS experiment has fit their observed single track chisquare distribution in 3 prong tau decays to the sum of two chisquare distributions: one (of fraction $1-f$) using spatial resolutions determined from calibration events, and one (of fraction f) having errors expanded by the factor R. The fit yields $f = 0.61 \pm 0.03$, and $R = 1.43 \pm 0.03$.

The incorrect assignment of vertex detector hits in 3 prong tau decays causes a systematic increase in the observed τ_τ because the reconstructed tracks are pulled closer together and appear to originate from a decay vertex downstream of the actual decay vertex. An illustration of the systematic increase in observed decay length caused by incorrect hit assignment[19] is given in Fig. 9. This figure plots the average decay length for 3 prong τ decays measured with the HRS detector, as a function of the number of vertex detector hits shared between the three tracks. The effect is striking, and the experimenters reject decays if any vertex hits are shared.

The Mark II pattern recognition program does not allow hits to be shared between tracks, but a similar effect can be observed by plotting the average decay distance $\bar{l}$ as a function of track separation as shown in Figure 10. Even though cuts on individual track quality have been applied, for closely spaced tracks hit misassignment occurs which causes $\bar{l}$ to increase. The Monte Carlo simulations also include these effects. But if the spatial resolution in the detector model is too optimistic, the simulation of this effect will be underestimated resulting in a lifetime measurement which is too large. Note that simply expanding the spatial errors to force χ^2 distributions in data and Monte Carlo model to agree does not fully correct for the bias due to misassigned hits.

An additional systematic error due to optimistic Monte Carlo detector models, which tends to cause τ_τ to be overestimated, exists for the impact parameter method. The impact parameter δ is given by $\delta = l \cdot sin(\phi)$ where l is the tau decay distance, and ϕ is the track angle to the tau direction in the plane perpendicular to the beam axis. Tracks from 3 prong decays with small ϕ are more likely to be close to other tracks and therefore suffer increased hit misassignment or hit inefficiency. Track quality cuts will reject a larger fraction of tracks with small ϕ and therefore small δ. If the track quality cut efficiency is lower in the data than in the idealized Monte Carlo model, then fewer tracks with small impact parameters will be rejected in the simulation causing the measured lifetime to be overestimated.

Each experiment assigns a systematic error to account for the known imperfections in the Monte Carlo model. In the Mark II, HRS, and MAC decay length method measurements of τ_τ, these bias uncertainties dominate the total systematic error. But these imperfections lead to errors which are of the same sign for all experiments. Averaging these measurements without taking this correlation into account will underestimate the systematic error. Thus, the difference between the world average value for B_e and the prediction from τ_τ is less significant than implied by the 1.7 standard deviation difference obtained above. This example illustrates the potential pitfalls of averaging measurements where the systematic error for each experiment is at least as large as the statistical error on the average.

5. Theoretical Predictions for B_e

Theoretical considers can in principle provide guidance towards the solution of the 1 prong problem. Theoretical predictions[2,3] for the largest one prong decay modes are given in Table 2. However, these predictions have been normalized to the measured leptonic branching ratios because of theoretical uncertainties in calculating the decay rates for some hadronic modes. The experimental measurements for B_ρ and B_π agree well with the predictions. Note that electroweak radiative corrections have recently been calculated[3] and are included in the predictions for B_ρ and B_π listed in Table 2. These corrections increase previous estimates[2] for B_ρ by 2.36% ($B_\rho/B_e = 1.26$ instead of 1.23) and decrease B_π by 1.0% (B_π/B_e=.601 instead of .607). One possible explanation of the discrepancy is that the world average values for B_e and B_μ are about 5% too low (i.e., B_e should be about 19%). Then the theoretical predictions for B_e, B_μ, B_ρ, and B_π would need to be increased by about 5%. This would, at least theoretically, explain the discrepancy. However, it would mean that the current world averages for B_e, B_μ, B_ρ, and B_π are low by about 3, 2, 2, and 1 standard deviations respectively.

An accurate and precise theoretical prediction for B_e would help considerably to clarify the 1 prong problem. The first predictions for heavy lepton branching fractions were made before the tau was discovered,[20] and for a sequential heavy lepton of mass m_τ, predicted B_e to be about 20%. Perturbative QCD calculations of B_e were first done[21] in 1977, and predicted B_e to be about 17 to 18%. In 1988, Braaten published[22] a precise prediction for B_e (19.0 ± 0.1%) based on a perturbative QCD calculation to order α_s^2. Unfortunately, the next order term (α_s^3) turned out to be very large and invalidated this precise prediction.[23] Although the theoretical calculations for B_e are currently too imprecise to help disentangle the one prong problem, it may turn out that measurements of B_e and τ_τ will yield the most accurate determinations of the QCD parameter $\Lambda_{\overline{ms}}$.[3,24,25]

6. Constrained Branching Fraction Measurements

Motivated by the one prong problem, four experiments have simultaneously measured sets of tau branching fractions subject to the constraint that the branching fractions sum to 1. Although, by definition, these measurements cannot exhibit the one prong problem, by comparing these results to the unconstrained measurements, one can hope to uncover clues to the origin of the discrepancy.

The PLUTO collaboration was the first to perform a constrained analysis,[26] but it suffered from low statistics and will not be considered here. The TPC experiment[27] used a much larger data sample but did not measure photons. The Mark II experiment[28] used a tagging technique where tau pair events were selected using one tau decay to tag the event while the other provided a relatively unbiased sample for study. The CELLO collaboration has recently announced results of their analysis[29] in which they analyze their tau event sample in two ways: 1) each decay is constrained to be in one of seven classes which approximately correspond to the exclusive decay modes; and 2) decays which have a low probability of being in any of the seven classes are rejected. We consider here only the results of their first analysis.

Table 6 gives the measured values of B_1, B_e, and B_μ for each constrained experiment, their average, and the difference between these averages and the world averages listed in Table 2. There is no evidence that most of the one prong discrepancy is due to errors in the world averages for B_1, B_e, or B_μ.

Table 7 gives the measured branching fractions of each constrained experiment for the modes $\tau^- \to \text{hadron}^-$ (≥ 0 neutrals) ν_τ and $\tau^- \to \text{hadron}^-$ (≥ 1 neutral) ν_τ, their averages, and the difference between these averages and the values from Table 2 used in the sum of exclusive 1 prong modes. For these modes, the constrained experiments are consistent with each other, but tend to be larger than the appropriate values derived from Table 2. This comparison suggests but in no way proves that one or more of the world averages for $B(\tau^- \to \rho^-\nu_\tau)$ or $B(\tau^- \to \pi^-(2\pi^0)\nu_\tau)$, or theoretical limits for $B(\tau^- \to \pi^-(2\pi^0)\nu_\tau)$, $B(\tau^- \to \pi^-(\geq 3\pi^0)\nu_\tau)$ or $B(\tau^- \to \pi^-(\geq 1\eta)(\geq 0\pi^0)\nu_\tau)$ are too small. Unfortunately, no single experiment has sufficient statistics to make a definitive statement.

7. Conclusions

After nearly half a decade, the tau one prong discrepancy remains unresolved. Since no single experiment has sufficient precision, the discrepancy is significant only if world averaged branching fractions are used. However, averaging experiments which are dominated by systematic errors is an unreliable procedure. To solve the problem, new high statistics experiments are needed. But as some recent tau branching fraction measurements have demonstrated, high statistics by itself is not sufficient; the new experiments must be designed to minimize systematic uncertainties.

Acknowledgements

I wish to thank G. Grindhammer, C. K. Jung, and M. L. Perl for helpful and stimulating discussions.

REFERENCES

1. Particle Data Group, G.P. Yost *et al.*, Phys. Lett. **204B**, 1 (1988).
2. F. J. Gilman and J. M. Rhie, Phys. Rev. **D31**, 1066 (1985); F. J. Gilman, Phys. Rev. **D35**, 3541 (1987).
3. W. J. Marciano and A. Sirlin, Phys. Rev. Lett. **61**, 1815 (1988).
4. T. N. Truong, Phys. Rev. **D30**, 1509 (1984).
5. C. Akerlof *et al.*, Phys. Rev. Lett. **55**, 570 (1985).
6. K. G. Hayes and M. L. Perl, Phys. Rev. **D38**, 3351 (1988).
7. S. Abachi *et al.*, ANL-HEP-PR-88-90, to be published in Phys. Rev. **D**.
8. H. J. Behrend *et al.*, Phys. Lett. **222B**, 163 (1989).
9. H. J. Behrend *et al.*, Phys. Lett. **114B**, 282 (1982).
10. H. J. Behrend *et al.*, Z. Phys. **C23**, 103 (1984).
11. Additional References for Table 4. PLUTO: Ch. Berger *et al.*, Z. Phys. **C28**, 1 (1985); TASSO: M. Althoff *et al.*, Z. Phys. **C26**, 521 (1985); MAC: E. Fernandez *et al.*, Phys. Rev. Lett. **54**, 1624 (1985); JADE: W. Bartel *et al.*, Phys. Lett. **161B**, 188 (1985); DELCO: W. Ruckstuhl *et al.*, Phys. Rev. Lett. **56**, 2132 (1986); MARK 2: W.B. Schmidke *et al.*, Phys. Rev. Lett. **57**, 527 (1986); TPC: H. Aihara *et al.*, Phys. Rev. **D35**, 1553 (1987).
12. B. Adeva *et al.*, Phys. Rev. **D38**, 2665 (1988).
13. B. Adeva *et al.*, Phys. Lett. **179B**, 177 (1986).
14. H. Albrecht *et al.*, Z. Phys. **C41**, 1 (1988).
15. For references to the experimental data, see summary tables in Reference 6.
16. H. Albrecht *et al.*, Z. Phys. **C41**, 405 (1988).
17. References for tau lifetime measurements:
    MARK II: G. Feldman *et al.*, Phys. Rev. Lett. **48**, 66 (1982); MAC: W. Ford *et al.*, Phys. Rev. Lett. **49**, 106 (1982); CELLO: H. J. Behrend *et al.*, Nucl. Phys. **B211**, 369 (1983); TASSO: M. Althoff *et al.*, Phys. Lett. **141B**, 264 (1984); MAC: E. Fernandez *et al.*, Phys. Rev. Lett. **54**, 1624 (1985); DELCO: D. E. Klem *et al.*, SLAC-Report-300, (1986), p.67; MARK II: D. Amidei *et al.*, Phys. Rev. **D37**, 1750 (1988); MAC: H. R. Band *et al.*, Phys. Rev. Lett. **59**, 415 (1987); HRS: S. Abachi *et al.*, Phys., Rev. Lett. **59**, 2519 (1987); CLEO: C. Bebek *et al.*, Phys. Rev. **D36**, 690 (1987); ARGUS: H. Albrecht *et al.*, Phys. Lett. **199B**, 580 (1987); TASSO: W. Braunschweig *et al.*, Z. Phys. **C39**, 331 (1988); JADE: C. Kleinwort *et al.*, Z. Phys.**C42**, 7 (1989).

18. Electroweak radiative corrections to this formula are at the level of $3 \cdot 10^{-4}$. See Reference 3.

19. C. K. Jung, Ph.D. Dissertation, Indiana University Report IUHEE#98, (1986), p.81.

20. Y. S. Tsai, Phys. Rev. **D4**, 2821 (1971); H. B. Thacker and J. J. Sakurai, Phys. Lett. **36B**, 103 (1971).

21. C. S. Lam and T. M. Yan, Phys. Rev. **D16**, 703 (1977); T. Appelquist in Particles and Fields, ed. by D. H.Boal and A. N. Kamal, Plenum Press New York, 1978, p.33.

22. E. Braaten, Phys. Rev. Lett. **60**, 1606 (1988).

23. E. Braaten, Phys. Rev. **D39**, 1458 (1989).

24. S. Narison and A. Pich, Phys. Lett. **211B**, 183 (1988).

25. Jon Pumplin, Michigan State University preprint MSUTH89/1, to be published in Phys. Rev. Lett.; Jon Pumplin, Michigan State University preprint MSUTH89/2, submitted to Phys. Rev. D.

26. Ch. Barger *et al.*, Z. Phys. **C28**, 1 (1985).

27. A. Aihara *et al.*, Phys. Rev. **D35**, 1553 (1987).

28. P. R. Burchat *et al.*, Phys. Rev. **D35**, 27 (1987).

29. H. J. Behrend *et al.*, paper submitted to the 1989 Lepton-Photon Symposium, Stanford, CA.

Table 1. World average τ topological branching fractions (from section 2 and Ref. 1).

Decay Mode	World Average (%)
B_1	86.0 ± 0.3
B_3	13.9 ± 0.3
B_5	0.15 ± 0.03
B_x	< 0.019 90% C.L.

Table 2. Summary of τ 1-Prong Branching Fractions (%).

Decay Mode	Experiment	Theory[a]
$e^- \nu \nu$	$17.7 \pm .4$	18.0
$\mu^- \nu \nu$	$17.7 \pm .4$	17.5
$\rho^- \nu$	$22.3 \pm .8$	22.7
$\pi^- \nu$	$10.8 \pm .6$	10.8
$K^-(\geq 0 \text{ neutrals})\nu$	$1.71 \pm .29$	
$K^{*-}\nu$, $K^{*-} \to \pi^-(2\pi^0 \text{ or } K_L)$	$.6 \pm .1$	
$\pi^-(2\pi^0)\nu$	7.4 ± 1.4[b]	$\leq 6.7 \pm .4$
$\pi^-(\geq 3\pi^0)\nu$		< 1.4[d]
$\pi^-(\geq 1\eta)(\geq 0\pi^0)\nu$[c]	< 0.9	$< .8$
Sum of measured modes		78.2 ± 1.8
Theoretical limits on unmeasured modes		< 2.2
Sum of exclusive modes		$< 80.4 \pm 1.8$
Measured 1-prong branching ratio		$86.0 \pm .3$
Difference		$> 5.6 \pm 1.8$

[a]Normalized to constrained fit to $e\nu\nu$ and $\mu\nu\nu$ measurements assuming $B_\mu = .973\ B_e$.

[b]Crystal Ball Collaboration, S. Lowe, SLAC-PUB-4449.

[c]Contribution to 1 prong mode only.

[d]Assumes 15% systematic error on the measured cross section for $e^+e^- \to 2\pi^+2\pi^-$.

Table 3. Published B_1 measurements by the HRS and CELLO Collaborations.

Experiment/Year	B_1 (%)	Energy (GeV)	$\int \mathcal{L} dt$ (pb^{-1})	Reference
HRS 1985	$86.9 \pm 0.2 \pm 0.3^*$	29	176	5
HRS 1989	$86.4 \pm 0.3 \pm 0.3$	29	291	7
CELLO 1982	84.0 ± 2.0	32–37	—	9
CELLO 1984	$85.1 \pm 2.8 \pm 1.3$ $85.2 \pm 2.6 \pm 1.3$	22 14	2.5 1.0	10
CELLO 1989	$84.9 \pm 0.4 \pm 0.3$	35–37	136	8

* The statistical error on this measurement was underestimated.

Table 4. Independent B_1 measurements included in the current world average. The references are listed in Ref. 11.

Experiment/Year	Measurement (%)	Combined Error	Weight
PLUTO 1985	$87.8 \pm 1.3 \pm 3.9$	± 4.1	.0036
TASSO 1985	$84.7 \pm 1.1^{+1.6}_{-1.3}$	$^{+1.9}_{-1.7}$	.0187
MAC 1985	$86.7 \pm 0.3 \pm 0.6$	± 0.7	.1238
JADE 1985	$86.1 \pm 0.5 \pm 0.9$	± 1.0	.0607
DELCO 1986	$87.9 \pm 0.5 \pm 1.2$	± 1.3	.0359
MARK II 1986	$87.2 \pm 0.5 \pm 0.8$	± 0.9	.0749
TPC 1987	$84.7 \pm 0.8 \pm 0.6$	± 1.0	.0607
HRS 1989	$86.4 \pm 0.3 \pm 0.3$	± 0.4	.3791
CELLO 1989	$84.9 \pm 0.4 \pm 0.3$	± 0.5	.2426
Average 86.0 ± 0.3			

Table 5. All published measurements of the tau lifetime in units of 10^{-13} sec. References to the experimental data are listed in Ref. 17.

Experiment/Year	Measurement	Combined Error	Weight
MARK II 1982	4.6 ± 1.9	± 1.9	0.0017
MAC 1982	4.9 ± 2.0	± 2.0	0.0005
CELLO 1983	$4.7^{+3.9}_{-2.9}$	$^{+3.9}_{-2.9}$	0.0005
TASSO 1984	$3.18^{+0.59}_{-0.75} \pm 0.56$	$^{+0.81}_{-0.94}$	—
MAC 1985	$3.15 \pm 0.36 \pm 0.40$	± 0.54	0.021
DELCO 1986	$2.63 \pm 0.46 \pm 0.20$	± 0.50	0.024
MARK II 1987	$2.88 \pm 0.16 \pm 0.17$	± 0.23	0.112
MAC 1987	3.09 ± 0.19	± 0.19	0.168
HRS 1987	$2.99 \pm 0.15 \pm 0.10$	± 0.18	0.188
CLEO 1987	$3.25 \pm 0.14 \pm 0.18$	± 0.23	0.117
ARGUS 1987	$2.95 \pm 0.14 \pm 0.11$	± 0.18	0.192
TASSO 1988	$3.06 \pm 0.20 \pm 0.14$	± 0.24	0.102
JADE 1989	3.01 ± 0.29	± 0.29	0.072
Average 3.027 ± 0.078			

Table 6. Measurements of B_1, B_e and B_μ (in %) from experiments which constrain the sum of measured branching fractions to be 1. The average of these measurements, the world average values (from Table 2) and their difference are also given.

Experiment	B_1	B_e	B_μ
TPC	$84.7 \pm 0.8 \pm 0.6$	$18.4 \pm 1.2 \pm 1.0$	$17.7 \pm 1.2 \pm 0.7$
MARK II	$86.9 \pm 1.0 \pm 0.7$	$19.1 \pm 0.8 \pm 1.1$	$18.3 \pm 0.9 \pm 0.8$
CELLO	$85.0 \pm 2.4 \pm 1.2$	$18.4 \pm 0.8 \pm 0.4$	$17.7 \pm 0.8 \pm 0.4$
Average	85.5 ± 0.7	18.6 ± 0.7	17.9 ± 0.6
World Average	86.0 ± 0.3	17.7 ± 0.4	17.7 ± 0.4
Difference	-0.5 ± 0.8	0.9 ± 0.8	0.2 ± 0.7

Table 7. Measurements of $B(\tau^- \to h^-$ (≥ 0 neutrals) $\nu_\tau)$ and $B(\tau^- \to h^-$ ($\geq$1 neutral) $\nu_\tau)$ (in %) from experiments which constrain the sum of measured branching fractions to be 1. Also listed are the average of these measurements, values for these modes used in the sum of exclusive 1 prong modes (from Table 2), and the difference of these two.

Experiment	$B(\tau^- \to h^-(\geq 0 \text{ neutrals})\ \nu_\tau)$	$B(\tau^- \to h^-(\geq 1 \text{ neutral})\ \nu_\tau)$
TPC	$48.6 \pm 1.2 \pm 0.9$	—
MARK II	$49.5 \pm 1.6 \pm 1.3$	$38.4 \pm 1.2 \pm 1.0$
CELLO	$48.9 \pm 2.1 \pm 1.0$	$36.6 \pm 1.9 \pm 0.9$
Average	48.9 ± 1.1	37.8 ± 1.3
Table 2 Value	$< 45.0 \pm 1.7$	$< 33.1 \pm 1.7$
Difference	$> 3.9 \pm 2.0$	$> 4.7 \pm 2.1$

FIGURE CAPTIONS

Fig. 1. Number of experimental publications of tau lifetime or branching fraction measurements by year.

Fig. 2. All published tau 1 prong branching fraction measurements. Points with solid symbols are used in the world average.

Fig. 3. Particle Data Group average values for the tau 1 prong topological branching fraction. The current 1989 world average (Table 4) is also shown.

Fig. 4. All published measurements of B_e. B_μ measurements are included by applying the $e-\mu$ universality constraint $B_\mu = .973 B_e$.

Fig. 5. All published measurements of B_ρ. The world average is shown as a vertical bar. The 1987 MARK II measurement is not used in the world average.

Fig. 6. All published measurements of B_π. The world average is shown as a vertical bar.

Fig. 7. Sum of the pull distributions for B'_e, B_π, and B_ρ.

Fig. 8. All published measurements of τ_τ. The world average is shown as a vertical bar.

Fig. 9. The mean tau decay distance for 3 prong tau decays as a function of the number of vertex chamber hits shared between tracks. This data is from the HRS experiment (Ref. 19).

Fig. 10. The mean tau decay distance for 3 prong tau decays as a function of the maximum angle ϕ_{ij} between any 2 of the 3 decay tracks in the plane perpendicular to the beam axis. This data is from the Mark II experiment at PEP.

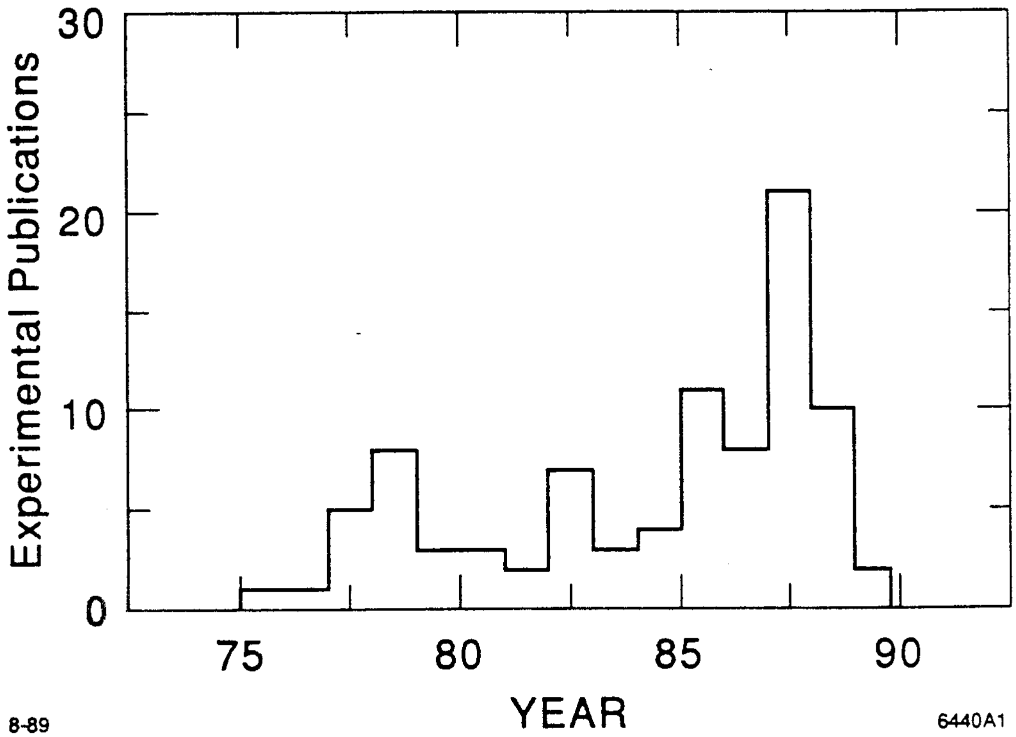

Experimental Publications
30
20
10
0
75
80
85
90
YEAR
8-89
6440A1

Fig. 1

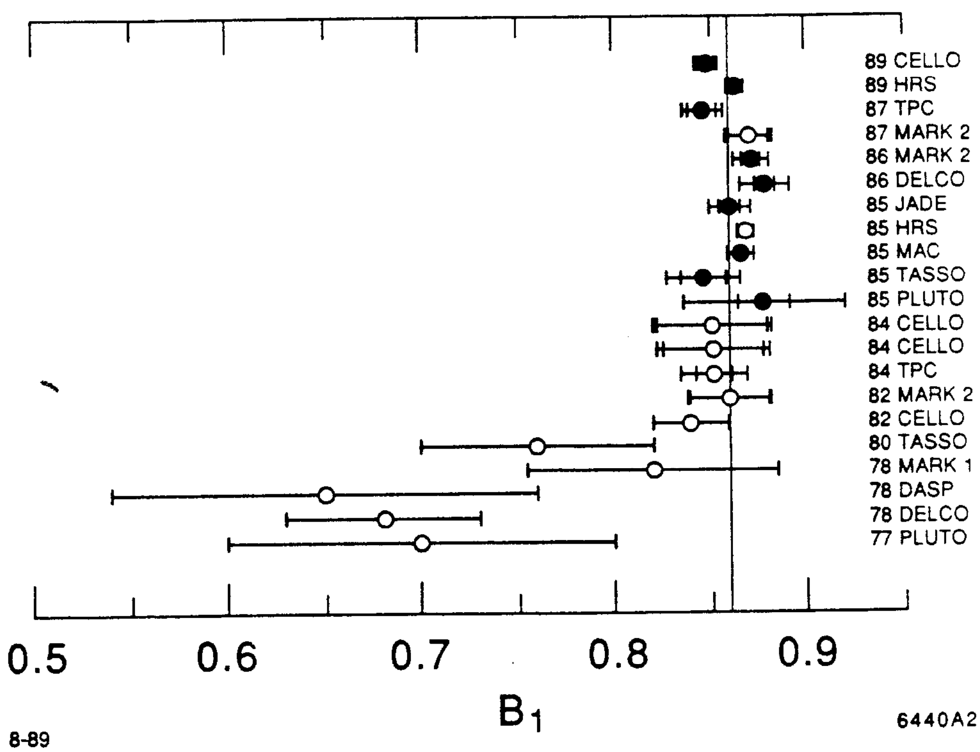
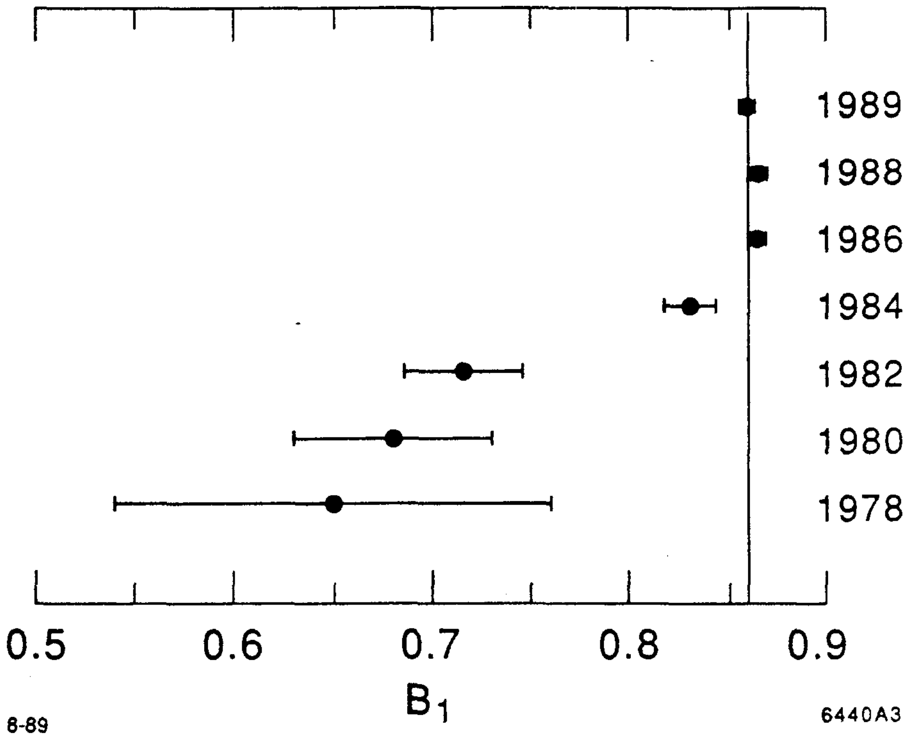
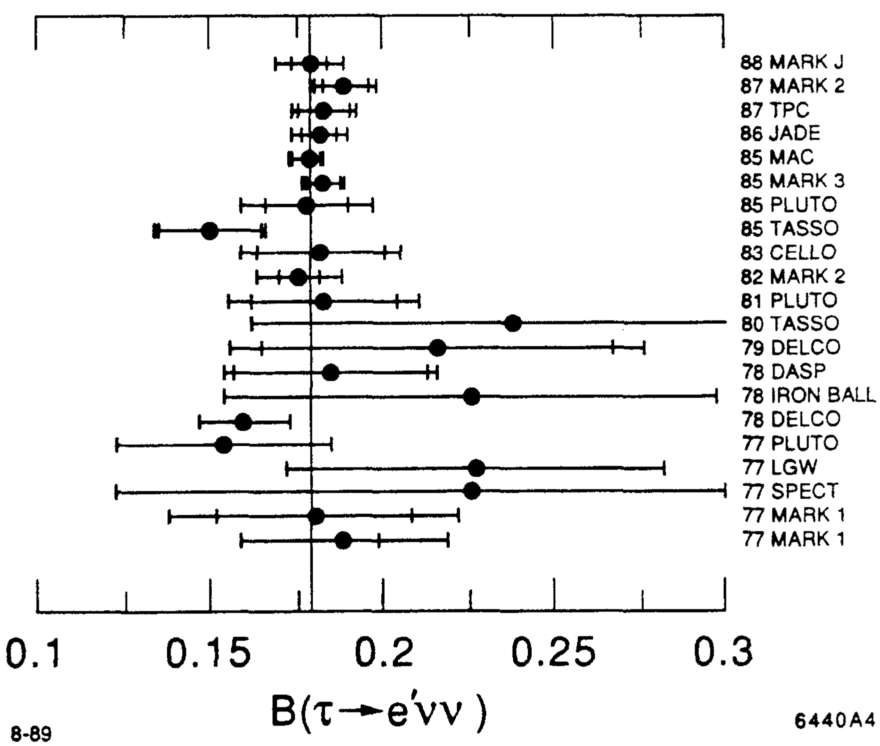

89 CELLO
89 HRS
87 TPC
87 MARK 2
86 MARK 2
86 DELCO
85 JADE
85 HRS
85 MAC
85 TASSO
85 PLUTO
84 CELLO
84 CELLO
84 TPC
82 MARK 2
82 CELLO
80 TASSO
78 MARK 1
78 DASP
78 DELCO
77 PLUTO
0.5
0.6
0.7
0.8
0.9
B1
8-89
6440A2

Fig. 2



1989
1988
1986
1984
1982
1980
1978
0.5
0.6
0.7
0.8
0.9
B_1
8-89
6440A3

Fig. 3



88 MARK J
87 MARK 2
87 TPC
86 JADE
85 MAC
85 MARK 3
85 PLUTO
85 TASSO
83 CELLO
82 MARK 2
81 PLUTO
80 TASSO
79 DELCO
78 DASP
78 IRON BALL
78 DELCO
77 PLUTO
77 LGW
77 SPECT
77 MARK 1
77 MARK 1
0.1
0.15
0.2
0.25
0.3
$B(\tau \rightarrow e'\nu\nu)$
8-89
6440A4

Fig. 4

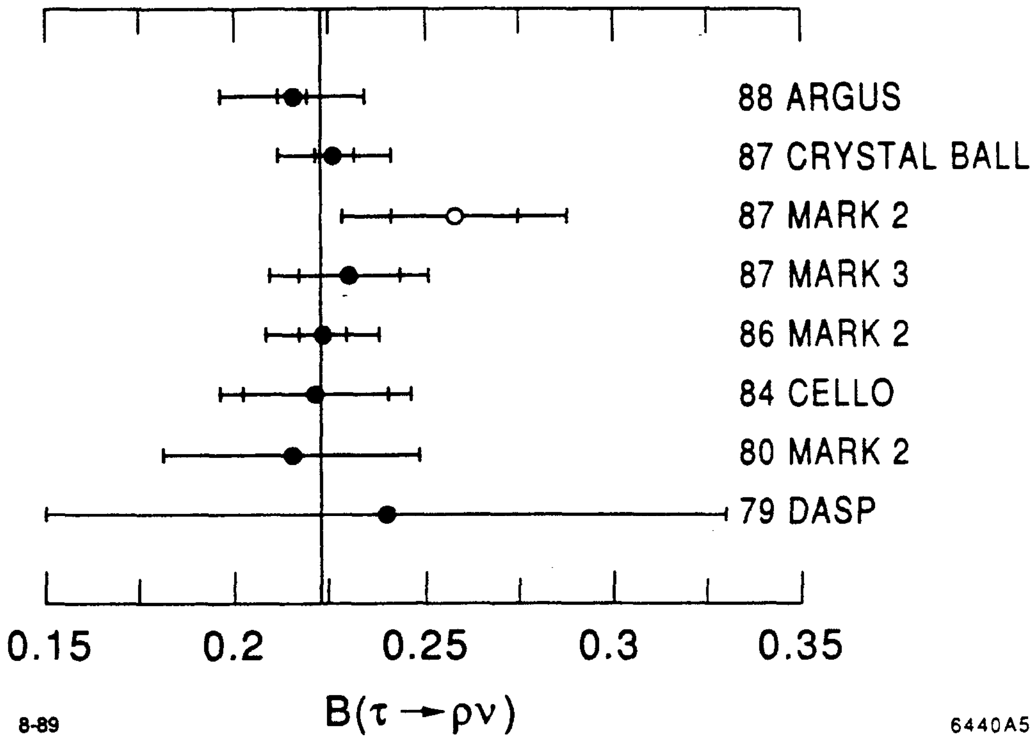

88 ARGUS
87 CRYSTAL BALL
87 MARK 2
87 MARK 3
86 MARK 2
84 CELLO
80 MARK 2
79 DASP
0.15
0.2
0.25
0.3
0.35
$B(\tau \rightarrow \rho\nu)$
8-89
6440A5

Fig. 5

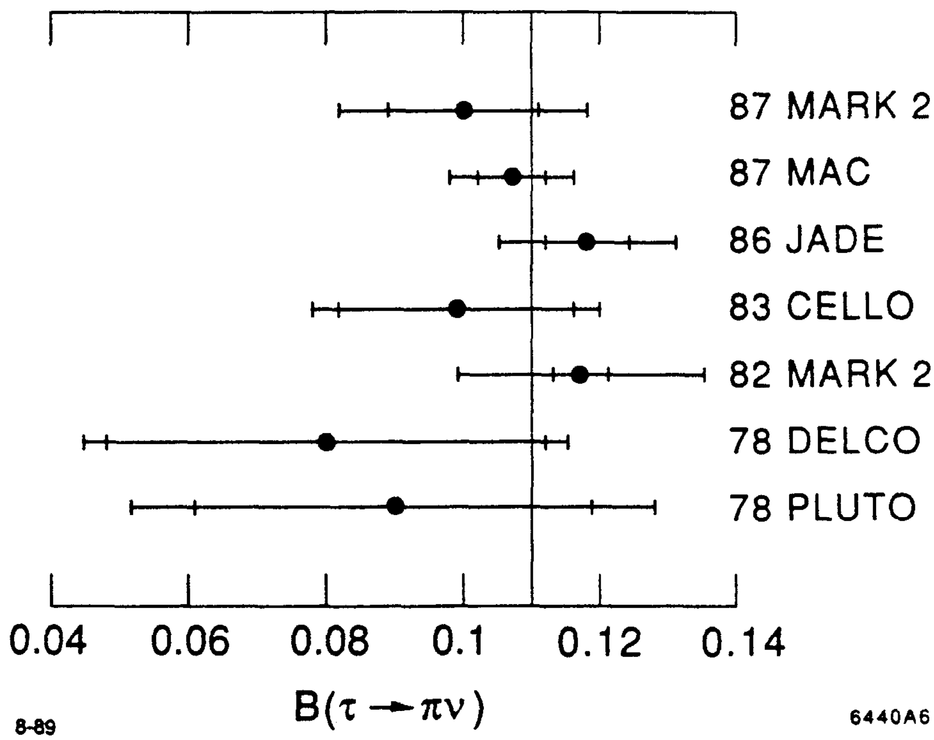
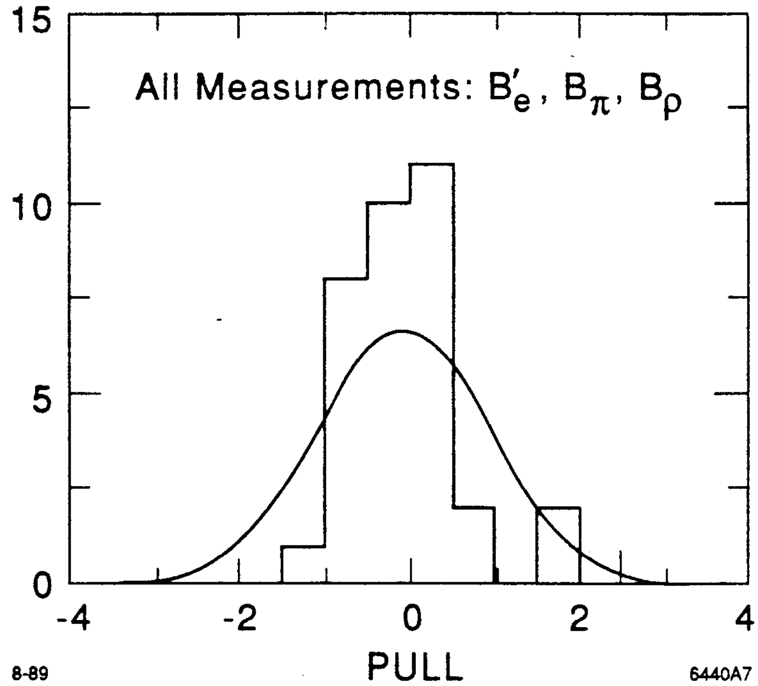
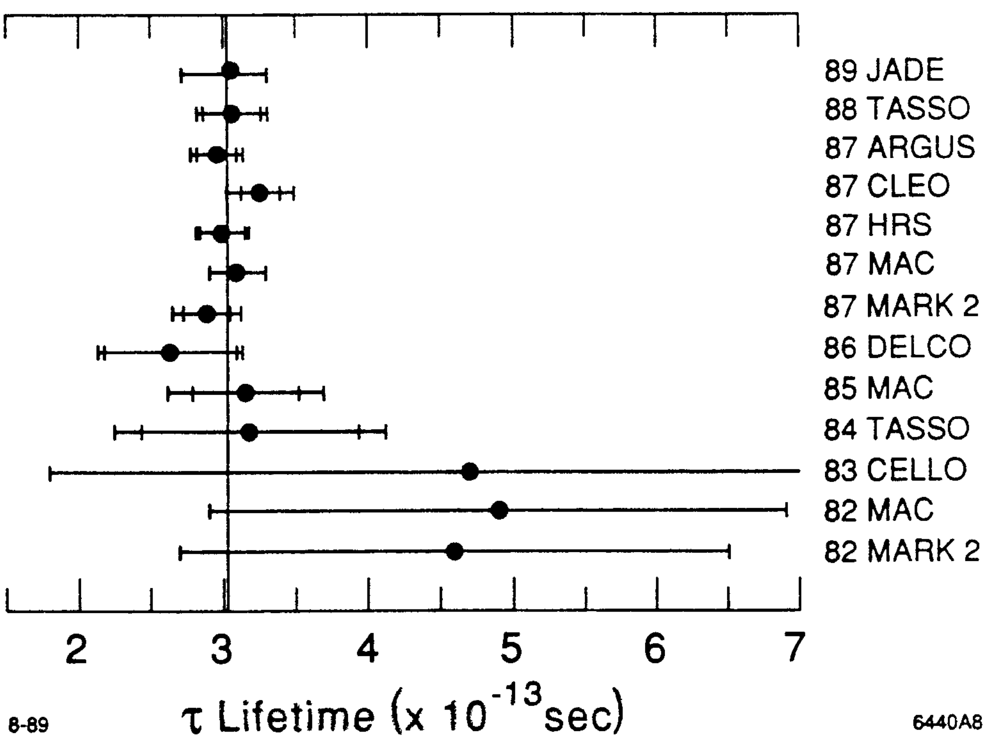

87 MARK 2
87 MAC
86 JADE
83 CELLO
82 MARK 2
78 DELCO
78 PLUTO
0.04
0.06
0.08
0.1
0.12
0.14
$B(\tau \rightarrow \pi\nu)$
8-89
6440A6

Fig. 6



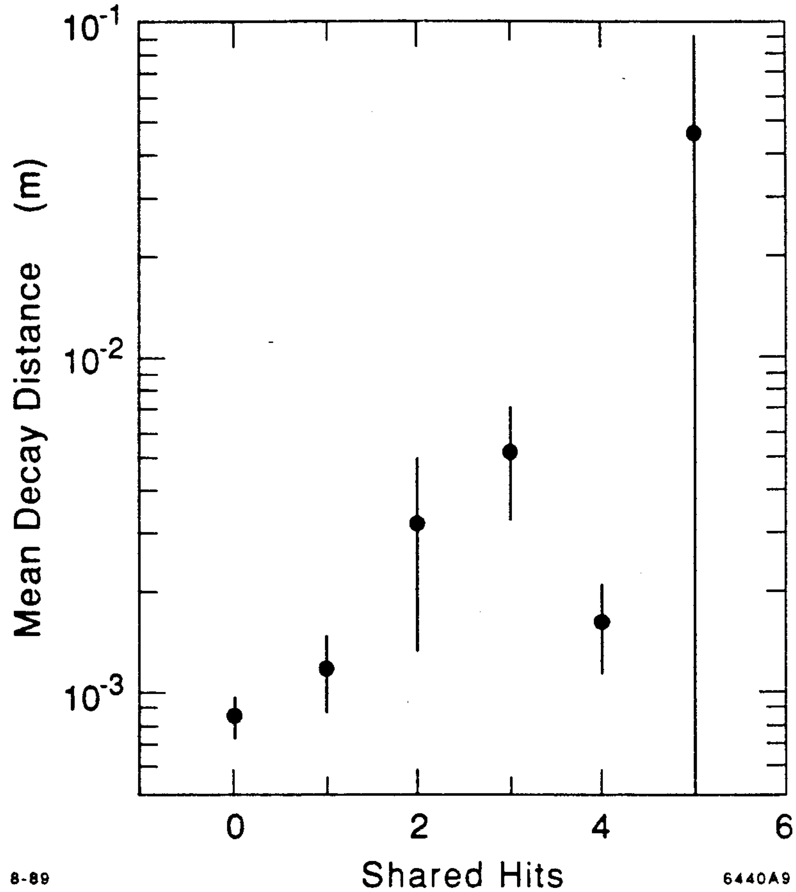
15
10
5
0
All Measurements: B'_e, B_π, B_ρ
-4
-2
0
2
4
PULL
8-89
6440A7

Fig. 7



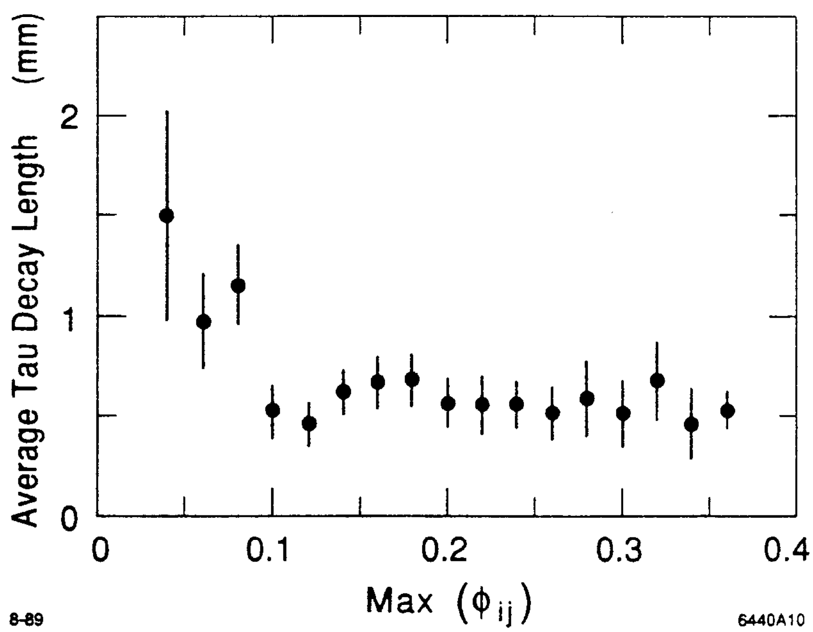
89 JADE
88 TASSO
87 ARGUS
87 CLEO
87 HRS
87 MAC
87 MARK 2
86 DELCO
85 MAC
84 TASSO
83 CELLO
82 MAC
82 MARK 2
2
3
4
5
6
7
τ Lifetime (x 10^{-13}sec)
8-89
6440A8

Fig. 8



10^{-1}
10^{-2}
10^{-3}
Mean Decay Distance (m)
0
2
4
6
Shared Hits
8-89
6440A9

Fig. 9



Average Tau Decay Length (mm)
0
1
2
0
0.1
0.2
0.3
0.4
Max (ϕ_{ij})
8-89
6440A10

Fig. 10