Comparison and summary of tau topological branching fractions

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After nearly two decades of work on topological branching fractions, it appears that an experimental consensus is forming. The new world average is 14.54 ± 0.20 .

1. INTRODUCTION

Topological branching fractions have played an important role in tau physics, especially in trying to understand the experimental consistency problem known as the "one-prong deficit". This decade-old problem was that the sum of the exclusive tau decays was not consistent with the measured topological branching fractions. It appears that recent precise data have resolved this inconsistency, which has been most evident in one-prong decays

Though the one-, three- and five-prong branching fractions cannot be predicted with any precision, Gilman and Rhie [1] showed that a great deal can be learned from the modes which can be predicted (such as $e\nu\nu$, $\mu\nu\nu$, $\pi\nu$, and $\rho\nu$) and isospin relations for other modes. Currently the most useful comparisons are between precise measurements of the topological branching fractions with the appropriate sums of exclusive modes.

2. HISTORY

The history of measurements of the three-prong branching fraction, B_3 [2], is illustrated in Fig. 1. The early measurements from SPEAR and DORIS were much larger than modern values, probably due to background from charmed-particle decays. These measurements are now discarded by the Particle Data Group (PDG) for this reason. More precise measurements became available in the early 1980's from PETRA and PEP

experiments. The CELLO collaboration [3] published a result of $15 \pm 2\%$ and the Mark II collaboration [4] found $14 \pm 2\%$. Though these results were limited by small event samples, they are in excellent agreement with recent precise measurements.

Figure 1. World-average values of the tau three-prong branching fraction as determined by the Particle Data Group and published in the Review of Particle Properties (RPP).

The situation began to change again once larger event samples became available at PEP

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and PETRA. In 1985, the MAC collaboration [5] published a result of $(13.3 \pm 0.3 \pm 0.6)\%$, followed soon by HRS [6] with $(13.0 \pm 0.2 \pm 0.3)\%$. The indication that the three-prong branching fraction might be smaller than 14% was soon reinforced by JADE [7] $(13.6 \pm 0.5 \pm 0.8)\%$, a new Mark II measurement [9] $(12.8 \pm 0.5 \pm 0.8)\%$ and a DELCO measurement [10] $(12.1 \pm 0.5 \pm 1.2)\%$. In order to indicate more clearly the recent history, we show just the situation from 1986 to the present in Fig. 2. The world average branching fraction reached a minimum in 1986 but has risen since then.

Figure 2. An expanded version of Fig. 1 covering only the recent history. The rising trend is now evident.

The trend of increasing B_3 began with a dissenting PEP “vote” from TPC [11] in 1987 $(15.1 \pm 0.8 \pm 0.6)\%$ and a more precise result from CELLO [12] $(15.0 \pm 0.4 \pm 0.3)\%$ in 1989. The trend has greatly accelerated with precise results from LEP experiments: L3 [14] $(14.4 \pm 0.6 \pm 0.3)\%$, ALEPH [16] $(14.35^{+0.40}_{-0.45} \pm 0.24)\%$ and OPAL [17] $(15.26 \pm 0.26 \pm 0.22)\%$. A new result from ALEPH [19] $(14.79 \pm 0.14 \pm 0.16)\%$ is even more precise. The situation with conflicting older and newer measurements is reflected clearly in the ideogram in Fig. 3, taken from the most recent Review of Particle Properties [20]. The inconsistency between the older measurements and the recent published ones is evidenced by the double peaking of the ideogram. The error is scaled by $S \equiv \sqrt{\chi^2/(N_{\text{meas}} - 1)}$ to account for

this inconsistency. We will discuss the individual contributions to the χ^2 in the next section. The results mentioned above and other less precise results are summarized in Fig. 4.

Figure 3. An ideogram from the latest RPP showing the various tau B_3 measurements. The inconsistency between measurements is evidenced by the double-peaked distribution.

3. COMPLICATIONS FROM K_S DECAYS

It would appear that the newer results over the past five years now provide a consistent picture of the three-prong branching fraction being about 1% larger than the value in 1986, a relative shift of nearly 10%. The actual discrepancy with the earlier results is even larger since most of the older measurements included $K_S \rightarrow \pi^+ \pi^-$ events with three-prong decays while the new LEP measurements include them with one-prong decays.

To understand the effect of K_S decays, I have read all of the published papers to try to understand how these decays were treated. The specific issue concerns whether a $K_S \rightarrow \pi^+ \pi^-$ is counted as zero or two tracks. Since most tau decays involving K_S 's have only one other charged track, this amounts to distinguishing whether these events are considered as one-prongs

or three-prongs [21]. This is an important issue since the branching fraction of such decays amounts to $(0.55 \pm 0.10)\%$ [24], about twice the magnitude of the systematic error of most recent measurements.

The process of determining how the K_S decays were treated was surprisingly frustrating. Many papers do not make clear what was done. In some analyses K_S decays may not have been included in the Monte Carlo (MC) simulation at all. In such cases K_S decays would have been partially included in both one-prong and three-prong samples, depending on details of track impact-parameter requirements. The PEP experiments MAC, HRS, DELCO and TPC included the K_S decays with three-prongs, while Mark II excluded them from the three-prong sample. Among PETRA experiments, JADE and TASSO seem to include them as three-prongs though they are not completely clear. I could not determine how CELLO treated these decays (this is important since CELLO has one of the more precise results). The situation was also unclear for the ARGUS measurement. It appears that all of the LEP experiments include the K_S decays with one-prongs, although the papers are not completely clear.

We seem to be developing a convention which will greatly simplify the topology classification in the future. The $K_S \rightarrow \pi^+\pi^-$ decay will be treated as zero tracks, allowing all decays of K^0 mesons to fall in the same event topology. This convention makes considerable sense for LEP experiments where most K_S decays are seen as clearly-reconstructed secondary vertices and $\sim 10\%$ of the K_S mesons live too long to be observed in the tracking detectors. Presumably by 1996, the PDG definition of B_3 will no longer include $2/9$ of the K^* decay, representing the contribution from $K_S \rightarrow \pi^+\pi^-$ events. Adopting this convention will require corrections for the older experiments or their removal if they did not make clear how these decays were handled.

To see the significance of the correction for K_S decays, we correct all pre-1990 measurements except Mark II and CELLO by -0.55% and include the latest ALEPH [19] and DELPHI [18] results. The double-peaking in Fig. 3 becomes even more pronounced. The world average would change from $(14.54 \pm 0.20)\%$ (Fig. 4) to $(14.43 \pm 0.24)\%$, with the scale factors increasing from 1.49 to 1.84. The χ^2 would increase to 40.6, corresponding to a

confidence level well below 0.1%. The largest contributions to the χ^2 would become HRS (12.2), MAC (6.3) OPAL (5.9) and DELCO (4.9). The recent LEP measurements keep the world average from being pulled down very much but the χ^2 becomes terrible, indicating the true level of disagreement between the old PEP measurements and the more modern ones.

4. CRITIQUE OF EXPERIMENTS

Can one learn anything from examining the papers closely as to a likely cause for this large discrepancy? There are various obvious differences between the newer LEP experiments and those of the PEP/PETRA era. The detectors themselves are now much more sophisticated. The most relevant part of the detectors for the topological branching fraction measurement is the tracking devices. MAC had a 10-layer main drift chamber with only 35 cm of tracking length! HRS had 15 layers and a tracking length of 80 cm. OPAL has a main drift chamber with 159 measurements over a radial extent of 160 cm, not including sophisticated wire and silicon vertex detectors which were largely absent in much of the PEP data. Other LEP detectors are fairly similar. There are also major differences between the environments at center-of-mass energies of 29 GeV and 90 GeV. It is possible at LEP to isolate tau events from $q\bar{q}$ and QED backgrounds with efficiency above 50% and little bias to the event topology. ALEPH recently has managed a selection efficiency of $\sim 90\%$ within the fiducial volume! At PEP, efficiencies were in the range 10-40%, and backgrounds were still several times larger than those at LEP. In Table 1, we compare the selection efficiency, background levels and assigned systematic errors for the MAC, HRS, Mark II, ALEPH and OPAL experiments. The tracking systematic error includes uncertainties from pair conversions, topology migration, interactions, and trigger. The Mark II measurement used only the 1-3 topology, thus requiring the luminosity and cross section to determine the branching fraction. They assigned an additional systematic error of 0.005 for uncertainty in the luminosity and cross section.

While it is clear that tau physics is much easier at LEP, that is not to say that it couldn't be done at PEP. Many PEP measurements had a precision of $\sim 5\text{-}10\%$ and agree with modern mea-

Table 1

Summary of various features of PEP and LEP measurements. Values for the 1-1 and 1-3 topologies are given separately where there is a difference.

Experiment	ϵ (%)	BG (%)	ϵ	Systematic errors in B_3		
	1-1/1-3	1-1/1-3		Tracking	τ BF	BG
MAC	22/38	2/4	0.002	0.004	0.002	0.002
HRS	11/26	8/6	0.002	0.001	0.002	0.001
Mark II	-/24	-/3	0.005	in ϵ	-	0.004
ALEPH	78	2/0.4	0.0007	0.0012	0.0007	0.0003
OPAL	57	1/0.2	0.0010	0.0016	in ϵ	0.0014

measurements. There were likely problems with these measurements which may not have affected other PEP analyses, perhaps since many other measurements normalized to the topological branching fractions in order to have cancelling systematic errors. One of the problems which was identified in MAC involves tracking difficulties. The number of events in which the topology was 1 vs. 2 was large and not well simulated by the MC. They assigned a 3% systematic error based on scanning events and trying to understand the difference between data and MC but it seems likely that this systematic error could have been underestimated. There are no such obvious problems one can point to in the HRS and Mark II measurements, though with these relatively low efficiencies, there was considerable reliance on the Monte Carlo and the simulations at that time were not as sophisticated as modern ones. We focus on the HRS measurement [13], since it is the PEP measurement with the smallest quoted errors and the largest contribution to the χ^2 . Though the momentum distribution of charged tracks was well simulated by Monte Carlo [25], the systematic error assigned for tracking was in fact smaller than that assigned by ALEPH and OPAL. Given the sophisticated systematics studies done by the latter experiments, not all of which were possible given the relatively crude MC's at PEP, it seems likely that the estimate by HRS of the tracking systematic error was underestimated. However we are looking for an effect larger than .01 in B_3 , while the assigned tracking error was .001. It seems unlikely that the error could have been underestimated by such a large factor.

Another possibility might be the underestimate of background in the one-prong sample, which would increase B_1 , thus decreasing B_3 . An underestimate of the background of about 6% would

be needed to cause a shift in B_3 by .01. It can be seen from the $\cos\theta$ distribution from the HRS electroweak interference analysis [26] that there is no evidence for a Bhabha-scattering background in excess of the calculated amount. The μ -pair and 2-photon backgrounds were larger and could have been underestimated, though there is no evidence of this. Another possibility concerns the selection criteria which were used to reject backgrounds. There was considerable dependence on the energy deposition in the lead-wire-chamber electromagnetic calorimeter for rejection of QED backgrounds. If this was not well simulated, the efficiency could have been overestimated. There is far too little information in any of the published HRS papers to evaluate whether this could explain such a large systematic effect, but it seems likely that this could have been a significant factor.

Thus while it is just not possible to determine the cause of the PEP-era low values for B_3 , there is little doubt that the new LEP measurements are much more reliable. It does seem highly likely in retrospect that the PEP measurements underestimated their systematic errors, giving them too large a weight in the world average and causing the double-peaking in Fig. 3.

5. PRESENT EXPERIMENTAL STATUS

In Fig. 4, we summarize the present experimental situation for B_3 . We have included two unpublished results. One is a new precise ALEPH analysis [19] and the other a result from DELPHI [18]. The world average is now back to 14.5%, just where it was after the 1982 Mark II and CELLO results, but with an uncertainty that is a factor of seven smaller. Due to the inconsistency between

Figure 4. A summary of the most recent three-prong branching fraction measurements from each collaboration. The weight of each measurement in the weighted average and the scale factor S are also given.

the old and new results, the error scaled by S is very nearly the same as that of the ALEPH measurement alone.

The LEP measurements now have 69% of the weight in the world average, though two are more than two years old. We can expect updated analyses from these LEP experiments soon. If the results are consistent with those already published, the 1996 ideogram will be much more like a single peak with a shoulder on the low side and the discrepancy pretty much fully resolved.

The situation with the five-prong branching fraction is shown in Fig. 5. Here all measurements are consistent. From this and the value of B_3 given above, we calculate the one-prong branching fraction, $B_1 = (85.36 \pm 0.20)\%$.

The comparison between inclusive and exclusive measurements is also now in good shape. The sum of the exclusive three-prong modes is $(14.40 \pm 0.27)\%$ [22], in excellent agreement with the value in Fig. 4. The sum of the exclusive one-prong modes is $(84.66 \pm 0.38)\%$ [22], leaving a 1-prong deficit of 0.70 ± 0.43 , a discrepancy of only 1.6σ .

6. CONCLUSIONS

There is a large discrepancy between old and new topological branching fraction measure-

Figure 5. A summary of five-prong branching fraction measurements. The weight of each measurement in the weighted average and the scale factor S are also given.

ments. It is not easy to understand what may have caused such small branching fractions as reported by several PEP experiments. However, more recent measurements, especially new measurements from LEP experiments, are beginning to resolve the situation in favor of larger values of B_3 . This increase has played a substantial role in the disappearance of the tau one-prong problem.

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