Proposed explanation of τ lepton decay puzzle: Discrepancy between the measured and the theoretical τ lifetimes

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I propose an explanation of the current discrepancy between the measured world average value and the theoretical value of the τ lepton lifetime. I argue that there exist common systematic errors in many of the experiments that use three-prong τ decays for the lifetime measurement. These systematic effects always shift the measurement towards longer lifetimes, and are caused by the small opening angle of three-prong τ decays and limited tracking chamber ability to resolve nearby hits. The theoretical τ lifetime agrees well with the measured world average value from the one-prong τ decays.

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The discrepancy between the measured world average value of the τ lepton lifetime and the theoretical value obtained from the current world average values of the τ mass and leptonic branching ratios is one of the few remaining puzzles in the framework of the standard model (SM). In this model, since the τ is a sequential lepton with known universal charged current couplings, its lifetime τ_τ is calculable, and directly related to the μ lifetime τ_μ. Neglecting the electron and neutrino masses, the lowest-order theoretical prediction for τ_τ in the standard model is [1]

$$\tau_\tau=\tau_\mu(m_\mu/m_\tau)^5 B_l/f ,$$

where $m_{\mu,\tau}$ are the masses of the μ and τ respectively, B_l is the τ leptonic branching ratio $B(\tau^-\to l^-\nu_\tau\bar{\nu}_l; l=e$ or $\mu)$, and f is a phase-space suppression factor which is unity for $l=e$ and 0.973 for $l=\mu$. When the 1990 Particle Data Group (PDG) world average values [2] of m_τ and B_e are used, the predicted value of τ_τ becomes $2.83\pm0.07\times10^{-13}$ s, which is about 1.9σ away from the 1990 world average value for the measured τ_τ of $3.03\pm0.08\times10^{-13}$ s. To express the discrepancy in a more convenient way, let us define R_g as the ratio of the two weak coupling constants g_τ^w and g_l^w squared which is a measure of lepton universality: namely,

$$R_g\equiv\left[\frac{g_\tau^w}{g_l^w}\right]^2=\left[\frac{m_\mu}{m_\tau}\right]^5\frac{\tau_\mu}{\tau_\tau}\frac{B_l}{f} ,$$

where g_e^w and g_μ^w are assumed to be identical, and are determined from μ decays. The discrepancy is then expressed as R_g (from B_e)$=0.935\pm0.034$. For combining the results from B_e and B_μ, one obtains R_g(1990 ave)$=0.950\pm0.031$ which is about 1.6σ away from unity. The discrepancy is not overwhelming. However, its persistence and the unusually large number of consistent experimental measurements demand a careful analysis of the situation, especially when new measurements of τ_τ and B_l from the CERN e^+e^- collider LEP and CLEO experiments [3] further confirm the discrepancy, R_g(1992 ave)$=0.948\pm0.023$, contrary to general expectations. In fact, the significance of the discrepancy has increased to 2.3σ with the addition of new measurements. The discrepancy suggests that the SM, or one or more of the experimental measurements of τ_τ, m_τ, and B_l is wrong.

If all the experimental measurements are correct, then a fundamental change is necessary in the SM to accommodate the observed discrepancy. The simplest theoretical explanation for the discrepancy involves the introduction of a heavy sequential fourth generation neutrino [4]. If such a neutrino exists [5] with its charged lepton partner L^-, which we assume is heavier than the neutrino, then the neutrino weak eigenstates ν_l ($l=e$, μ, τ, and L) could be a mixture of the mass eigenstates ν_i ($i=1,4$) in analogy with the quark sector. If such a heavy neutrino mixes only with ν_3,

$$\nu_\tau=\nu_3\cos\theta_{34}+\nu_4\sin\theta_{34} ,$$

the effect of the mixing would be to reduce all theoretical τ decay rates by $\cos^2\theta_{34}$ or, equivalently, increase the theoretical lifetime prediction by $1/\cos^2\theta_{34}$.

On the other hand, if the SM is correct, one or more of the experimental measurements must be wrong. Indeed, newly reported results on the m_τ [6] indicate that the previous world average value was off by about 7 MeV/c^2. However, such a change in m_τ reduces the significance of the discrepancy only slightly because the new measurements have significantly smaller errors than the previous measurements. Using the new average value of m_τ, 1777.0 ± 0.5 MeV/c^2, one obtains $R_g(1992)=0.964\pm0.021$ which is 1.7σ away from unity. Thus, the discrepancy still persists.

In this article, I argue that the systematic bias in τ_τ measurements is the root of the lifetime discrepancy puzzle. By revisiting a previous study [7], I show that there is a systematic bias towards longer lifetimes in the τ_τ measurement from three-prong decays which is probably common to most of the experiments.

In general, the τ_τ measurements can be classified into two categories: measurements from one-prong τ decays and measurements from three-prong τ decays. The one-prong τ decay lifetimes are measured with the so-called "impact parameter" method while the three-prong τ decays lifetimes are mostly measured with the "decay length" method [8]. Detailed descriptions of the τ lifetime measurement methods can be found elsewhere [3].

In principle, the τ_τ values measured from one- and three-prong decays should be equal. The topological complication of three-prong τ decays, however, introduces a unique systematic error to the τ_τ measurements that does not exist in one-prong decays. The systematic error results from nearby hits generated in the tracking detectors by the three charged particles in a τ decay.

The most obvious bias comes from "hit sharing" among the three reconstructed tracks. A "shared hit" is defined as a recorded drift time in drift chambers which is used in the reconstruction of two or more tracks. The hit sharing problem is particularly serious for the τ decays at high-energy colliders, since the decay particles have small opening angles due to the large Lorentz boost. The cylindrical drift chambers most commonly used at e^+e^- collider experiments measure the projected angle of tracks in the plane perpendicular to the beam axis, increasing the probability of hit sharing. (Most previous experiments have used some type of high-resolution gas drift chambers to measure the τ lifetime. The use of silicon type vertex detectors or similarly fine grained high-resolution vertex detectors for the τ lifetime measurement has been so far minimal.) Since most of the experiments use single-hit electronics readout systems for the drift time measurements, if two or more charged particles pass through the same drift cell, only the information on the shortest drift time can be recorded, resulting in a source of bias in tracking. Because of the limited detector resolution there is no *a priori* way to determine to which track a shared hit should be assigned. Thus, many track fitters simply try all possible combinations to minimize the χ^2 of the fit. Usually, if the χ^2 contribution of a hit is too large, the hit is dropped from the fit. Consequently, if two tracks are separated by more than the chamber resolution limit, the confusion is, in principle, resolved and the hit is assigned to the track to which it makes a smaller χ^2 contribution; otherwise the hit is assigned to both tracks, which I define as a shared hit. It should be noted that even when a distinct hit for each track is detected, incorrect assignments can still occur. For experiments that used multihit electronics readout systems, the same problem exists within the two track resolution limit.

Including a misassigned hit in track fitting introduces a distortion in the track trajectory. Ironically, the problem is especially severe in the vertex chambers which are constructed mainly for the purpose of measuring lifetimes and are located very near the beam interaction points. For obvious geometrical reasons, hits are shared more often in the vertex layers, and because of its good resolution and proximity to the beam axis, a misassigned hit in the vertex layers can cause a large shift in a track trajectory when extrapolated to the beam interaction region. It is straightforward to show that when hit sharing occurs between the tracks from a decaying particle whose lifetime we wish to measure, it always results in a longer measured decay length and thus long lifetime measurements regardless of the type of lifetime measurement method used. To simplify the problem, consider a case when two nearby reconstructed tracks share a hit. Since the hit is the shorter of the two hits generated by the particles, the track with a misassigned hit will be pulled toward the other, resulting in an apparent longer decay length [9]. In general, hit sharing among the three tracks from τ decay usually results in a longer lifetime. (See Fig. 1.)

I examined this hit sharing effect in detail by using the three-prong τ decays and the $D^0(D^0 \to K\pi)$ decay event samples in the data obtained by the High Resolution Spectrometer (HRS) experiment at the SLAC e^+e^- storage ring PEP operated in the e^+e^- center-of-mass energy ($E_{\text{c.m.}}$) at 29 GeV. A detailed description of the HRS detector can be found elsewhere [10,11].

The three-prong τ decay events used for the study were selected with a one- versus three-prong topological cut. Thus, if any hit sharing occurred, it would be among the three-prong τ decay tracks. In Fig. 2, the mean decay length of the τ candidates measured with the decay length method is plotted against the number of shared hits, counting all combinations between any two of the three tracks in the vertex detector layers. The plot shows clearly an increase in decay length as the number of shared hits increases. It also shows that the error becomes large as shared hits increase. It reflects a lack of statistics for those bins but also the fact that as the number of shared hits increase the fluctuation in the measured decay length increases.

With the $D^0 \to K\pi$ events, I examined the effect of the hit sharing between a daughter track of the D^0 and a nearby spectator track that does not come from the D^0 decay. In this case, we expect the daughter tracks would be pulled to either direction, resulting in random fluctuations in the measured decay lengths. When the mean decay length of the D^0 is plotted against the number of shared hits between a daughter and a spectator track, no

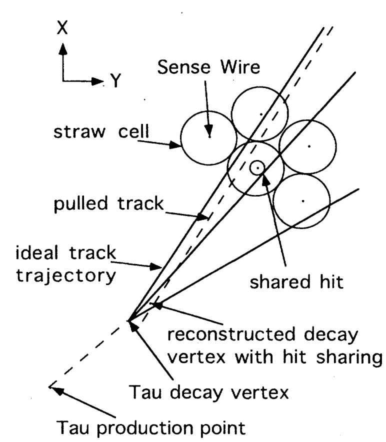

FIG. 1. Graphical description of the effect of hit sharing: The reconstructed track of the particle with the longer drift distance is pulled toward the one with the shorter drift distance when the shorter drift time is used in the reconstruction of both tracks.

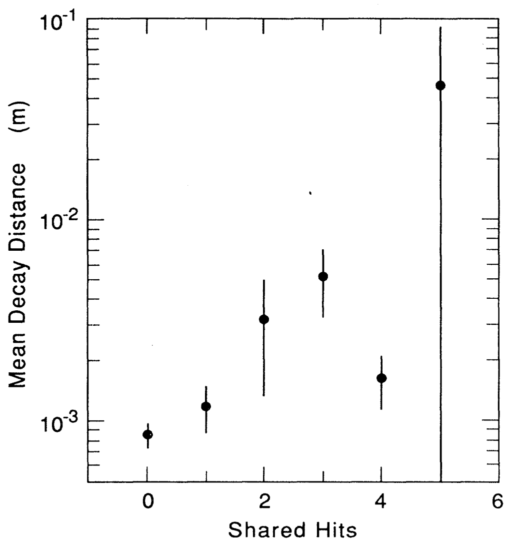

FIG. 2. Number of shared hits vs τ mean decay length for three-prong τ decays: The error bars reflect possible systematic errors associated with track reconstruction as well as the statistical errors. The typical event by event error in the measured decay length is about 1 mm.

particular trend for longer or shorter measured mean decay length is observed.

A similar study of measured τ_τ decay lengths was done by using the data obtained by the Mark II experiment at PEP [12]. The Mark II pattern recognition program does not allow hits to be shared between tracks; i.e., a hit is assigned to only the track to which it contributes the smallest χ^2. Nonetheless, a similar bias can be observed by plotting the mean decay length as a function of the angle ϕ_{ij} between tracks projected in the plane perpendicular to the beam axis as shown in Fig. 10 of Ref. [12]. The distribution shows that the decay length is constant (about 600 μm) within errors for ϕ_{ij} greater than 0.1 radian, while it is greater than 1 mm for ϕ_{ij} less than 0.1 radian.

The amount of "raw bias" caused by these effects is large. However, it can be substantially reduced after cuts on such things as track quality, decay length, and decay length error, and after error scaling in lifetime fitting, even if such procedures are not designed specifically to remove the events with these effects. The net amount of remaining bias depends on the details of the experimental

TABLE I. All statistically independent published τ lifetime measurements from one-prong τ decays.

Experiment	Measurement	Combined error
MAC 1985	3.15±0.36±0.40	0.54
MAC 1987	2.97±0.26±0.14	0.30
JADE 1989	2.89±0.33±0.26	0.42
DELPHI 1991	3.21±0.36±0.16	0.39
OPAL 1991	2.93±0.13±0.13	0.18
L3 1991	3.18±0.28±0.37	0.46
ALEPH 1992	2.90±0.16	0.16

TABLE II. All statistically independent published τ lifetime measurements from three-prong τ decays.

Experiment	Measurement	Combined error
Mark II 1982	4.60±1.90	1.90
MAC 1982	4.90±2.00	2.00
CELLO 1983	$4.70\pm^{3.90}_{2.90}$	$^{+3.90}_{-2.90}$
Mark II 1987	2.88±0.16±0.17	0.23
MAC 1987	3.16±0.26±0.10	0.28
HRS 1987	2.99±0.15±0.10	0.18
CLEO 1987	3.25±0.14±0.18	0.23
ARGUS 1987	2.95±0.14±0.11	0.18
TASSO 1988	3.06±0.20±0.14	0.24
JADE 1989	$3.09\pm^{0.35}_{0.34}\pm0.11$	0.37
DELPHI 1991	3.10±0.31±0.09	0.32
OPAL 1991	3.27±0.17±0.11	0.20
L3 1991	3.02±0.36±0.21	0.42
CLEO 1991	3.10±0.15±0.07	0.17
ALEPH 1992	2.94±0.25±0.11	0.27

apparatus and the analysis method used. For some measurements, the remaining bias may be negligible. For others it may not.

In principle, one could correct for this effect. The perfect Monte Carlo simulation of each experiment should naturally reflect these effects. But too optimistic and simplified detector models, especially those that do not simulate correctly the tails of the hits and interference among the multihits can result in underestimation of the effects. Thus, the best way to completely avoid the bias is to identify and remove the offending events directly from the final data sample. This, of course, reduces the available statistical power of each experiment. Traditionally, when disagreement between the Monte Carlo simulation and the data is observed, one increases the estimated measurement uncertainty to account for unknown systematic errors. Therefore, usually the bias is, in a sense, correctly accounted for in the form of systematic errors for each experiment. The problem arises when the weighted world average is made by combining each measurement assuming independent systematic errors, since the bias due to the hit sharing is common to most of the measurements from three-prong decays and has the same sign.

TABLE III. Various averages of the τ_τ measurements: The average values are obtained by using all statistically independent measurements. The measurements by the Mark II (1982), MAC (1982), and CELLO (1983) experiments are excluded from the relevant averages, following the PDG recipe.

Average	Average measured lifetime
World 1990	3.03±0.08
World 1992	3.03±0.06
One-prong 1990	2.98±0.22
One-prong 1992	2.96±0.10
Three-prong 1990	3.03±0.09
Three-prong 1992	3.07±0.07
Three-prong PEP/PETRA	3.01±0.11
Three-prong LEP	3.13±0.14

TABLE IV. Various R_g values obtained from averages of τ_τ measurements. For 1990 averages, the 1990 PDG values of B_l were used in the calculation.

Average	$R_g(m_\tau=1784.1)$	$R_g(m_\tau=1777.0)$
World 1990	0.956±0.031 (1.6σ)	0.966±0.030 (1.1σ)
World 1992	0.948±0.023 (2.3σ)	0.964±0.021 (1.7σ)
Three-prong 1992	0.935±0.025 (2.6σ)	0.954±0.024 (1.9σ)
One-prong 1992	0.970±0.035 (0.8σ)	0.990±0.035 (0.3σ)

In light of the above argument and assuming no specific corrections are made to the τ_τ measurements for the hit sharing effect, the following three general predictions can be made. The first is that the world average τ_τ value measured from three-prong τ decays should be longer than the average value measured from one-prong τ decays. The second is that for comparable detector resolution the τ_τ value measured at LEP energies should be longer than the value measured at energies reached at PEP and the DESY e^+e^- collider PETRA, since at LEP the τ's are produced with higher Lorentz boost resulting in smaller opening angles and thus more hit sharing. The third is that if a finely grained high-resolution tracker, such as a silicon vertex detector, with enough layers to provide a significant weight to track fitting is used, a shorter value for τ_τ will be observed.

In Tables I and II, all published one- and three-prong τ_τ measurements are compiled separately. As can be seen, the lifetimes measured from three-prong τ decays dominate the current world average. In Table III, various averaged values of the τ_τ have been calculated using all published measurements. Although the statistical significance is not compelling, one can see some degree of confirmation of the above predictions, except the third, for which available measurements to date are few: The world average value of τ_τ has not changed with inclusion of new results from the LEP and CLEO experiments but the error has become smaller; the average value of τ_τ measured from three-prong decays is longer than the average value measured from one-prong decays; and the average three-prong τ_τ measured at LEP experiments is longer than the average three-prong τ_τ (1990) measured at PEP and PETRA experiments. In Table IV, various values of R_g are summarized for the m_τ values of the 1990 average (PDG) and the new 1992 average, respectively. As can be seen, the one-prong averages agree much better with the lepton universality for both m_τ values than the three-prong averages.

In conclusion, I argue that the cause of the τ decay puzzle, the discrepancy between the measured and the theoretical τ lifetime, comes from the experimental bias in the τ lifetime measurements of three-prong τ decays. The world average value of the measured τ lifetime is biased towards a longer lifetime due to the biased measurements from three-prong τ decays. Presently, measurements from three-prong τ decays dominate the world average value for the τ lifetime, while the theoretical τ lifetime agrees well with the measured world average value from the one-prong τ decays. The current R_g value obtained using only the one-prong decays is 0.990±0.035, in excellent agreement with lepton universality.

Without properly accounting for the bias in the three-prong τ lifetime measurements, I predict the lifetime discrepancy will not be resolved in the near future even with new precise measurements on the τ mass, the leptonic branching ratio, or the lifetime.

I strongly recommend that experimentalists who still have access to data should reconsider earlier analyses keeping in mind the points made in this paper. I also suggest that the Particle Data Group should separate the lifetime measurements into two groups: one-prong measurements and three-prong measurements.

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