τ BRANCHING FRACTIONS

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Since the previous edition of this *Review*, there have been 11 published papers that have contributed to the τ Listings, including 5 each from the BaBar and Belle collaborations. Six of these papers have provided new upper limits on the branching fractions for neutrinoless τ-decay modes. Of the 59 neutrinoless τ-decay modes in the τ Listings, 2 are new and 24 have had improved limits set. The upper limits have been reduced by factors that range between 1.2 and 8.8 with the average reduction being a factor of 2.7.

There are now 22 measurements and 12 upper limits from Belle and BaBar on branching fractions of conventional τ-decay modes, up from 1 measurement and 3 upper limits in the 2006 edition of this Review. Nine of these measurements are used in the constrained fit to τ branching fractions, and 16 are for τ-decay modes for which older non-B-factory measurements exist. For those 16 measurements, the new B-factory measurements have on average about forty times the number of events as the most precise earlier measurements, and the statistical uncertainties on the B-factory measurements are on average about eight times smaller. However, the systematic uncertainties now greatly exceed the statistical uncertainties of all B-factory branching fraction measurements of major τ-decay modes. For example, the average ratio of systematic to statistical uncertainty of the B-factory measurements of τ branching fractions larger than 10^{-3} is 10.4, while the average ratio for branching fractions smaller than 10^{-4} is 0.8. Thus, the total uncertainty on the branching fraction measurements from B-factories is on average only about 3.6 times smaller than the previous most precise non-B-factory measurements.

Comparing the 16 B-factory τ branching fraction measurements to the earlier non-B-factory measurements reveals interesting systematic discrepancies between the two sets of measurements. Figure 1 shows a histogram of the normalized difference ((B-factory value minus non-B-factory value)/estimated uncertainty in the difference) for the 16 measurements. The value used for the non-B-factory measurement is the value listed in the latest edition of this *Review* prior to the first B-factory measurement for that decay mode. Fifteen of the 16 B-factory branching fraction measurements are smaller than the non-B-factory values. The average normalized difference between the two sets of measurements is -1.36 (-1.68 for the 8 Belle measurements and -1.05 for the 8 BaBar measurements).

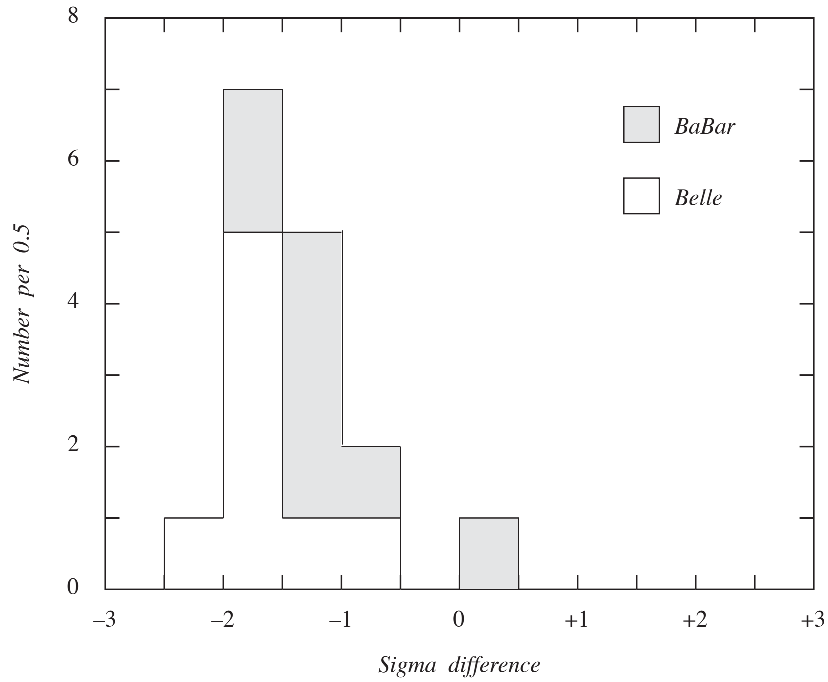

Figure 1: Distribution of the normalized difference between the 16 B-factory measurements of conventional τ-decay branching fractions and non-B-factory measurements. The Belle and BaBar collaborations have each published 8 measurements.

The cause of this discrepancy remains to be understood.

The constrained fit to τ branching fractions: The Lepton Summary Table and the List of τ-Decay Modes contain branching fractions for 119 conventional τ-decay modes and upper limits on the branching fractions for 32 other conventional τ-decay modes. Of the 119 modes with branching fractions, 82 are derived from a constrained fit to τ branching fraction data. The goal of the constrained fit is to make optimal use of the experimental data to determine τ branching fractions. For example, the branching fractions for the decay mode $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ is determined mostly from experimental measurements of the branching fraction for $\tau^- \to h^-h^-h^+\pi^0\nu_\tau$ and measurements of exclusive branching fractions for 3-prong modes containing charged kaons and 1 π^0.

Branching fractions from the constrained fit are derived from a set of basis modes. The basis modes form an exclusive set whose branching fractions are constrained to sum exactly to one. The set of selected basis modes expands as branching fraction measurements for new τ-decay modes are published. The number of basis modes has expanded from 12 in the year 1994 fit to 31 in the 2002 through 2010 fits. The 31 basis modes selected for the 2010 fit are listed in Table 1. See the 1996 edition of this *Review* [1] for a complete description of our notation for naming τ-decay modes and the selection of the basis modes. For each edition since the 1996 edition, the changes in the selected basis modes from the previous edition are described in the τ Branching Fractions Review. Figure 2 illustrates the basis mode branching fractions from the 2010 fit.

In selecting the basis modes, assumptions and choices must be made. For example, we assume the decays $\tau^- \to \pi^-K^+\pi^- \geq 0\pi^0\nu_\tau$ and $\tau^- \to \pi^+K^-K^- \geq 0\pi^0\nu\tau$ have negligible branching fractions. This is consistent with standard model predictions for τ decay, although the experimental limits for these branching fractions are not very stringent. The 95% confidence level upper limits for these branching fractions in the current Listings are $\mathrm{B}(\tau^- \to \pi^-K^+\pi^- \geq 0\pi^0\nu_\tau) < 0.25\%$ and $\mathrm{B}(\tau^- \to \pi^+K^-K^- \geq 0\pi^0\nu_\tau) < 0.09\%$, values not so different from measured branching fractions for allowed 3-prong modes containing charged kaons. Although our usual goal is to impose as few theoretical constraints as possible so that the world averages and fit results can be used to test the theoretical constraints (*i.e.*, we do not make use of the theoretical constraint from lepton universality on the ratio of the τ-leptonic branching fractions $\mathrm{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)/\ \mathrm{B}(\tau^- \to e^-\overline{\nu}_e\nu_\tau) = 0.9726$), the experimental challenge to identify charged prongs in 3-prong

Table 1: Basis modes and fit values(%) for the 2010 fit to τ branching fraction data.

$e^-\overline{\nu}_e\nu_\tau$	17.85 ± 0.05
$\mu^-\overline{\nu}_\mu\nu_\tau$	17.36 ± 0.05
$\pi^-\nu_\tau$	10.91 ± 0.07
$\pi^-\pi^0\nu_\tau$	25.51 ± 0.09
$\pi^-2\pi^0\nu_\tau$ (ex. K^0)	9.29 ± 0.11
$\pi^-3\pi^0\nu_\tau$ (ex. K^0)	1.04 ± 0.07
$h^-4\pi^0\nu_\tau$ (ex. K^0, η)	0.11 ± 0.04
$K^-\nu_\tau$	0.696 ± 0.023
$K^-\pi^0\nu_\tau$	0.429 ± 0.015
$K^-2\pi^0\nu_\tau$ (ex. K^0)	0.065 ± 0.023
$K^-3\pi^0\nu_\tau$ (ex. K^0, η)	0.049 ± 0.023
$\pi^-\overline{K}^0\nu_\tau$	0.84 ± 0.04
$\pi^-\overline{K}^0\pi^0\nu_\tau$	0.40 ± 0.04
$\pi^-K^0_SK^0_S\nu_\tau$	0.024 ± 0.005
$\pi^-K^0_SK^0_L\nu_\tau$	0.12 ± 0.04
$K^-K^0\nu_\tau$	0.159 ± 0.016
$K^-K^0\pi^0\nu_\tau$	0.159 ± 0.020
$\pi^-\pi^+\pi^-\nu_\tau$ (ex. K^0, ω)	9.00 ± 0.06
$\pi^-\pi^+\pi^-\pi^0\nu_\tau$ (ex. K^0, ω)	2.70 ± 0.08
$K^-\pi^+\pi^-\nu_\tau$ (ex. K^0)	0.287 ± 0.016
$K^-\pi^+\pi^-\pi^0\nu_\tau$ (ex. K^0, η)	0.077 ± 0.012
$K^-K^+\pi^-\nu_\tau$	0.140 ± 0.005
$K^-K^+\pi^-\pi^0\nu_\tau$	0.0061 ± 0.0025
$h^-h^-h^+2\pi^0\nu_\tau$ (ex. K^0, ω, η)	0.10 ± 0.04
$h^-h^-h^+3\pi^0\nu_\tau$	0.023 ± 0.007
$3h^-2h^+\nu_\tau$ (ex. K^0)	0.0839 ± 0.0035
$3h^-2h^+\pi^0\nu_\tau$ (ex. K^0)	0.0178 ± 0.0027
$h^-\omega\nu_\tau$	1.99 ± 0.08
$h^-\omega\pi^0\nu_\tau$	0.41 ± 0.04
$\eta\pi^-\pi^0\nu_\tau$	0.139 ± 0.010
$\eta K^-\nu_\tau$	0.0161 ± 0.0011

τ decays is sufficiently difficult that experimenters have been

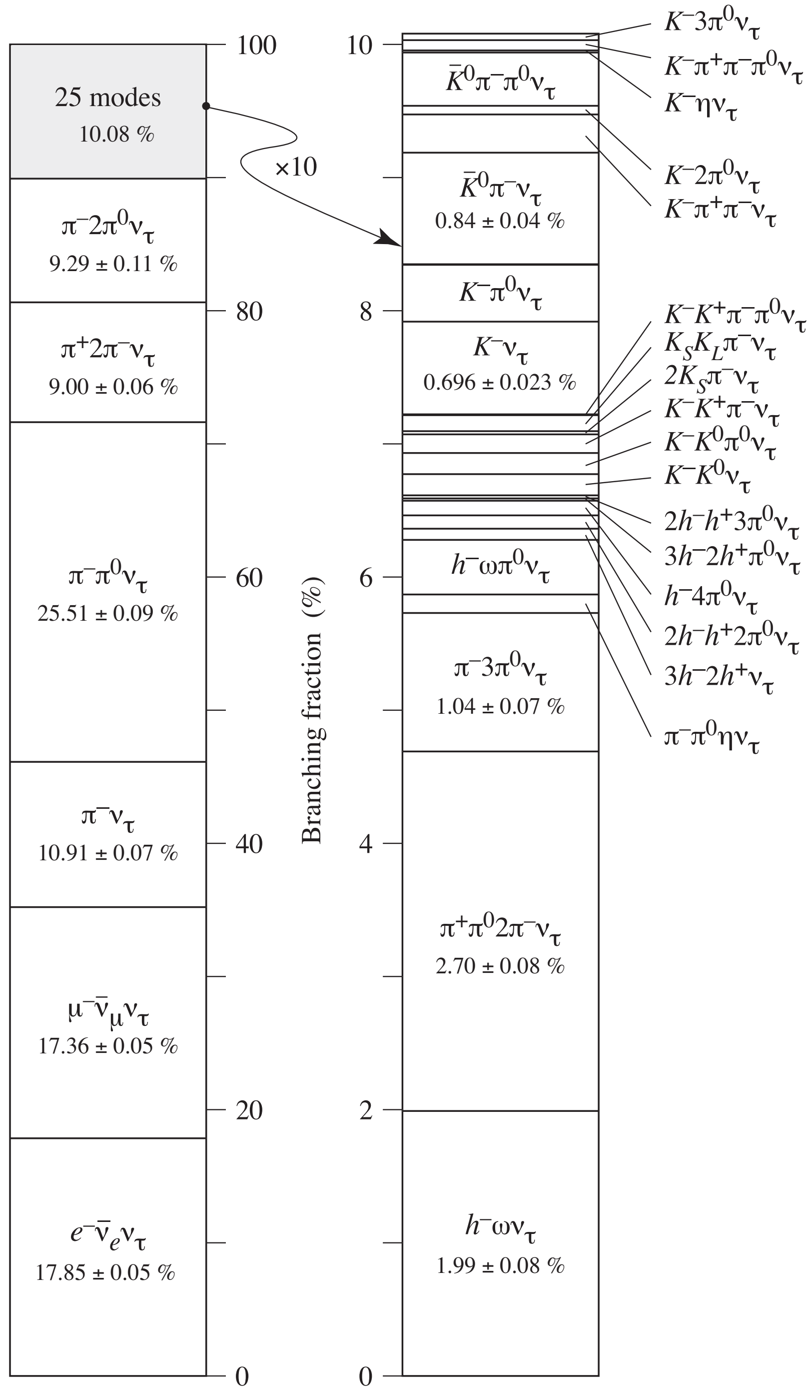

Figure 2: Basis mode branching fractions of the τ. Six modes account for 90% of the decays, 25 modes account for the last 10%. The list of excluded intermediate states for each basis mode has been suppressed.

forced to make these assumptions when measuring the branching fractions of the allowed decays. We are constrained by the assumptions made by the experimenters.

There are several τ-decay modes with small but well-measured (> 2.5 sigma from zero) branching fractions [2] which cannot be expressed in terms of the selected basis modes and are therefore left out of the fit:

$$\begin{aligned}
&\mathrm{B}(\tau^- \to \pi^- K^0_S K^0_L \pi^0 \nu_\tau) &&= (3.1 \pm 1.2) \times 10^{-4} \\
&\mathrm{B}(\tau^- \to 2K^- K^+ \nu_\tau) &&= (0.158 \pm 0.018) \times 10^{-4} \\
&\mathrm{B}(\tau^- \to \eta K^- \pi^0 \nu_\tau) &&= (0.48 \pm 0.12) \times 10^{-4} \\
&\mathrm{B}(\tau^- \to \eta \overline{K}^0 \pi^- \nu_\tau) &&= (0.93 \pm 0.15) \times 10^{-4}.
\end{aligned}$$

Certain components of other small but well-measured τ-decay modes cannot be expressed in terms of the selected basis modes and therefore are also left out of the fit:

$$\begin{aligned}
&\mathrm{B}(\tau^- \to \eta \pi^- \pi^0 \pi^0 \nu_\tau) \times \\
&\quad \mathrm{B}(\eta \to \gamma\gamma \text{ or } \eta \to \pi^+\pi^-\gamma \text{ or } \eta \to 3\pi^0) = (1.1 \pm 0.4) \times 10^{-4}, \\
&\mathrm{B}(\tau^- \to \eta \pi^- \pi^+ \pi^- \nu_\tau) \times \\
&\quad \mathrm{B}(\eta \to \gamma\gamma \text{ or } \eta \to \pi^+\pi^-\gamma) = (0.72 \pm 0.05) \times 10^{-4}, \\
&\mathrm{B}(\tau^- \to \phi K^- \nu_\tau) \times \\
&\quad \mathrm{B}(\phi \to K^0_S K^0_L \text{ or } \phi \to \eta\gamma) = (0.13 \pm 0.01) \times 10^{-4}, \\
&\mathrm{B}(\tau^- \to f_1(1285) \pi^- \nu_\tau) \mathrm{B}(f_1(1285) \to \rho^0 \gamma) = (0.20 \pm 0.06) \times 10^{-4}, \\
&\mathrm{B}(\tau^- \to h^- \omega \pi^0 \pi^0 \nu_\tau) \mathrm{B}(\omega \to \pi^0 \gamma) = (0.12 \pm 0.04) \times 10^{-4}, \\
&\mathrm{B}(\tau^- \to 2h^- h^+ \omega \nu_\tau) \mathrm{B}(\omega \to \pi^0 \gamma) = (0.10 \pm 0.02) \times 10^{-4}.
\end{aligned}$$

The sum of these excluded branching fractions is $(0.07 \pm 0.01)\%$. This is near our goal of 0.1% for the internal consistency of the τ Listings for this edition, and thus for simplicity we do not include these small branching fraction decay modes in the basis set.

Beginning with the 2002 edition, the fit algorithm has been improved to allow for correlations between branching fraction measurements used in the fit. If only a few measurements are correlated, the correlation coefficients are listed in the footnote for each measurement. If a large number of measurements are correlated, then the full correlation matrix is listed in the footnote to the measurement that first appears in the τ Listings. Footnotes to the other measurements refer to the first measurement. For example, the large correlation matrices for the branching fraction measurements contained in Refs. [3,4] are listed in Footnotes to the $\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{\rm total}$ and $\Gamma(h^-\nu_\tau)/\Gamma_{\rm total}$ measurements respectively. Sometimes experimental papers contain correlation coefficients between measurements using only statistical errors without including systematic errors. We usually cannot make use of these correlation coefficients.

The 2010 constrained fit has a χ^2 of 102.9 for 103 degrees of freedom up from 95.7 for 100 degrees of freedom in the 2008 fit. Two basis-mode branching fractions changed by more than 1.0 σ from their 2008 values, $B(\eta\pi^-\pi^0\nu_\tau)$ and $B(\eta K^-\nu_\tau)$, due to new measurements by the Belle Collaboration [5] of τ-decay modes containing $\eta' s$.

Overconsistency of Leptonic Branching Fraction Measurements: To minimize the effects of older experiments which often have larger systematic errors and sometimes make assumptions that have later been shown to be invalid, we exclude old measurements in decay modes which contain at least several newer data of much higher precision. As a rule, we exclude those experiments with large errors which together would contribute no more than 5% of the weight in the average. This procedure leaves five measurements for $B_e \equiv B(\tau^- \rightarrow e^-\overline{\nu}_e\nu_\tau)$ and five measurements for $B_\mu \equiv B(\tau^- \rightarrow \mu^-\overline{\nu}_\mu\nu_\tau)$. For both B_e and B_μ, the selected measurements are considerably more consistent with each other than should be expected from the quoted errors on the individual measurements. The χ^2 from the calculation of the average of the selected measurements is 0.34 for B_e and 0.08 for B_μ. Assuming normal errors, the probability of a smaller χ^2 is 1.3% for B_e and 0.08% for B_μ.

References

1. R.M. Barnett *et al.* (Particle Data Group), *Review of Particle Physics*, Phys. Rev. **D54**, 1 (1996).
2. See the τ Listings for references.
3. S. Schael *et al.* (Aleph Collab.), Phys. Rep. **421**, 191 (2005).
4. J. Abdallah *et al.* (Delphi Collab.), Eur. Phys. J. **C46**, 1 (2006).

5. K. Inami *et al.* (Belle Collab.), Phys. Lett. **B672**, 209 (2009).