PROCEEDINGS OF SCIENCE

$|V_{us}|$ and Charged Lepton Universality from τ Decays

Ian M. Nugent[*†]
University of Victoria/TRIUMF
E-mail: inugent@triumf.ca

τ decays provide a unique opportunity to make precision measurements of the weak interaction between the first and second generation of quarks, the Cabibbo-Kobayashi-Maskawa matrix (CKM) element $|V_{us}|$, and tests charged lepton universality, the assumption that all leptons have the same coupling strength to the gauge bosons.We present the recent measurements of τ decays from BELLE and *BABAR* and the improvements in determining $|V_{us}|$ and testing lepton universality.

The Xth Nicola Cabibbo International Conference on Heavy Quarks and Leptons,
October 11-15, 2010
Frascati (Rome) Italy

*Speaker.
†On behalf of the *BABAR* and BELLE Collaborations

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PoS(HQL 2010)015

1. τ Decay Measurements from BELLE and *BABAR*

The general strategy used at B-Factories to select clean sample of $\tau^+\tau^-$ events is to split the event into two hemisphere using the thrust in the CM frame. One hemispheres is required to have an isolated electron or muon from $\tau \to e\nu_\tau\overline{\nu}_e$ or $\tau \to \mu\nu_\tau\overline{\nu}_\mu$ to tag the event, while the other hemisphere, the signal hemisphere, is required to decay hadronically. Particle identification is applied to the charged tracks and selection of γs, π^0s and ηs are applied to identify the hadronic decay mode.

The *BABAR* Collaboration has published a measurement of $BR(\tau^- \to K^-\pi^0\nu_\tau)$ [1]. This analysis used a lepton tag with one well reconstructed π^0 and one kaon identified in the signal hemisphere. The branching fraction was measured to be $BR(\tau^- \to K^-\pi^0\nu_\tau)$=$(4.16 \pm 0.03 \pm 0.18) \times 10^{-3}$.

BABAR and BELLE have both measured $\tau^- \to K^0_S\pi^-\nu_\tau$, where the *BABAR* result is preliminary [2] and the BELLE result is published[3]. In this analysis, the signal hemisphere was required to contain a K^0_S reconstructed from a $\pi^+\pi^-$ pair and a bachelor pion. In the $\tau^- \to K^0_S\pi^-\pi^0\nu_\tau$ channel, the signal hemisphere was also required to contain a π^0 reconstructed from two photons[2]. BELLE measured $BR(\tau^- \to K^0_S\pi^-\nu_\tau)$=$(8.08 \pm 0.04 \pm 0.26) \times 10^{-3}$, while *BABAR* measured $BR(\tau^- \to K^0_S\pi^-\nu_\tau)$ =$(8.40 \pm 0.04 \pm 0.23) \times 10^{-3}$ and $\tau^- \to K^0_S\pi^-\pi^0\nu_\tau$=$(3.42 \pm 0.06 \pm 0.15) \times 10^{-3}$.

Both the BELLE and *BABAR* Collaborations have measured $\tau^- \to h^-h^-h^+\nu_\tau$ where h has been identified as a pion or kaon[4, 5]. After selecting the event with a leptonic tag and three charged tracks in the signal hemisphere, particle identification was applied and a matrix technique was used to extract the branching fractions shown in Table 1. The *BABAR* paper also measured $BR(\tau^- \to \pi^-\phi\nu_\tau)$=$(3.42 \pm 0.55 \pm 0.25) \times 10^{-5}$, $BR(\tau^- \to K^-\phi\nu_\tau)$=$(3.39 \pm 0.20 \pm 0.28) \times 10^{-5}$ and $BR(\tau^- \to K^-K^-K^+\nu_\tau\ [ex.\ \phi]) < 2.5 \times 10^{-6}$ at 90% CL. whereas BELLE measured $BR(\tau^- \to K^-\phi\nu_\tau)$=$(4.06 \pm 0.25 \pm 0.26) \times 10^{-5}$ in [6]

Table 1: The measured $\tau^- \to h^-h^-h^+\nu_\tau$ branching fractions.

Decay Mode	BELLE	*BABAR*
$BR(\tau^- \to \pi^-\pi^-\pi^+\nu_\tau\ [ex.\ K^0_s])$	$(8.42 \pm 0.01^{+0.26}_{-0.25}) \times 10^{-2}$	$(8.83 \pm 0.01 \pm 0.13) \times 10^{-2}$
$BR(\tau^- \to K^-\pi^-\pi^+\nu_\tau\ [ex.\ K^0_s])$	$(3.30 \pm 0.01^{+0.16}_{-0.17}) \times 10^{-3}$	$(2.73 \pm 0.02 \pm 0.09) \times 10^{-3}$
$BR(\tau^- \to K^-\pi^-K^+\nu_\tau)$	$(1.55 \pm 0.010^{+0.06}_{-0.05}) \times 10^{-3}$	$(1.346 \pm 0.010 \pm 0.036) \times 10^{-3}$
$BR(\tau^- \to K^-K^-K^+\nu_\tau)$	$(3.29 \pm 0.17^{+0.19}_{-0.20}) \times 10^{-5}$	$(1.58 \pm 0.13 \pm 0.12) \times 10^{-5}$

Recently, the BELLE collaboration has published a paper on precision measurements of τ decays containing an η[7]. In this paper, the signal hemisphere and π^0 and η are reconstructed from two photons, where the $\tau^- \to K^-\eta\nu_\tau$ used the additional η to $\pi^-\pi^+\pi^0$ decay mode. Using a fit of the η invariant mass, BELLE measured $BR(\tau^- \to K^-\eta\nu_\tau)$=$(1.48 \pm 0.05 \pm 0.09) \times 10^{-4}$, $BR(\tau^- \to K^-\pi^0\eta\nu_\tau)$=$(4.6 \pm 1.1 \pm 0.4) \times 10^{-5}$, and $BR(\tau^- \to K^0_s\pi^-\eta\nu_\tau)$=$(4.4 \pm 0.7 \pm 0.2) \times 10^{-5}$. For the $\tau^- \to K^*(892)^-\eta\nu_\tau$ decays the ηs are selected within a mass window, and a fit is applied to the $K^0_s\pi^-$ and $K^-\pi^0$ invariant mass to extract $BR(\tau^- \to K^*(892)^-\eta\nu_\tau)$=$(1.34 \pm 0.12 \pm 0.09) \times 10^{-4}$.

The *BABAR* Collaboration has recently published measurements of the one prong decay channels: $\tau \to e\nu_\tau\overline{\nu}_e$; $\tau \to \mu\nu_\tau\overline{\nu}_\mu$; $\tau \to \pi\nu_\tau$ and $\tau \to K\nu_\tau$ [8]. This was a blind analysis that used a

$\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ decay to tag, instead of the typical leptonic tag, and required an isolated signal track in the signal hemisphere that was topology consistent with coming from a one prong τ decay. A high purity selection is achieved by applying a tight particle identification criteria to suppress cross-feed between channels and other τ backgrounds. The backgrounds, cross-feed and particle identification are carefully estimated using a variety of Monte Carlo and data control samples. To reduce systematics that are common between channels, *BABAR* measured the $BR(\tau \to \mu\nu_\tau\overline{\nu}_\mu)/BR(\tau \to e\nu_\tau\overline{\nu}_e)$ =$(0.9796 \pm 0.0016 \pm 0.0035)$, $BR(\tau \to \pi\nu_\tau)/BR(\tau \to e\nu_\tau\overline{\nu}_e)$ =$(0.5945\pm0.0014\pm0.0061)$, $BR(\tau \to K\nu_\tau)/BR(\tau \to e\nu_\tau\overline{\nu}_e)$ =$(0.03882\pm0.00032\pm0.00056)$ and $BR(\tau \to K\nu_\tau)/BR(\tau \to \pi\nu_\tau)$ =$(0.06531 \pm 0.00056 \pm 0.00093)$. Using the world average $BR(\tau \to e\nu_\tau\overline{\nu}_e)$ =$(17.82 \pm 0.05) \times 10^{-2}$, the branching fractions $BR(\tau \to \mu\nu_\tau\overline{\nu}_\mu)$ =$(17.46 \pm 0.09) \times 10^{-2}$, $BR(\tau \to \pi\nu_\tau)$ =$(10.59 \pm 0.11) \times 10^{-2}$ and $BR(\tau \to K\nu_\tau)$ =$(6.92 \pm 0.12) \times 10^{-3}$ were determined.

2. Cabibbo-Kobayashi-Maskawa matrix element $|V_{us}|$ from τ

The CKM matrix element $|V_{us}|$ can be determined from τ decays using multiple techniques. One technique to extract $|V_{us}|$ from τ is to use flavor breaking difference with Finite Energy Sum Rules to extract $|V_{us}|$:

$$\frac{R_{\tau,strange}}{|V_{us}|^2} - \frac{R_{\tau,nonstrange}}{|V_{ud}|^2} = \delta R_{\tau,SU3\ breaking}$$

where $R_{\tau,strange} = \Gamma(\tau^- \to X_{strange}\nu_\tau)/\Gamma(\tau \to e\nu_\tau\overline{\nu}_e)$ is the strange hadronic width, $R_{\tau,nonstrange} = \Gamma(\tau^- \to X_{nonstrange}\nu_\tau)/\Gamma(\tau \to e\nu_\tau\overline{\nu}_e)$ is the nonstrange hadronic width and $\delta R_{\tau,SU3\ breaking}$ is the theoretical SU(3)flavor breaking correction determined using Operator Product Expansion (OPE). Using the HFAG values shown in Table 2, which combine the recent measurements from BELLE and *BABAR* with previous τ results, one obtains $|V_{us}| = 0.2188 \pm 0.0023$. The FESR approach for extracting $|V_{us}|$ has theoretical errors which range from 0.23%-0.47% depending on the FESR weight. This is the smallest theoretical error of the τ decay methods and smaller than the theoretical error from K_{l3} decays (0.58%)[9] and K_{l2} decays (0.5%)[10]. If the strange branching fractions and spectral functions are updated with the data currently available at BELLE and *BABAR* this method has the potential for making the most precise measurement of $|V_{us}|$ [11].

Another method which can be used to determine $|V_{us}|$ from τ decays is from the ratio:

$$\frac{BR(\tau \to K\nu_\tau)}{BR(\tau \to \pi\nu_\tau)} = \frac{f_K^2|V_{us}|^2}{f_\pi^2|V_{ud}|^2}\frac{\left(1-\frac{m_K^2}{m_\tau^2}\right)^2}{\left(1-\frac{m_\pi^2}{m_\tau^2}\right)^2}(1+\delta_{LD}),$$

where $f_K/f_\pi = 1.189 \pm 0.007$ [12] is determined from lattice QCD, $|V_{ud}|$ [13], and the long-distance correction $\delta_{LD} = (0.03 \pm 0.44)\%$ is estimated [14] using corrections to $\tau \to h\nu_\tau$ and $h \to \mu\nu_\mu$ [15, 16]. This method is orthogonal to the inclusive sum of strange τ decays approach and has a theoretical uncertainty of 0.5%. Using this method, *BABAR* [8] determined $|V_{us}| = 0.2255 \pm 0.0024$. This value is consistent with CKM unitarity [13] and 2.5σ higher than $|V_{us}|$ from the inclusive sum of strange τ decays.

A third method for determining $|V_{us}|$ from τ decays is from the $BR(\tau^- \to K^-\nu_\tau)$ directly.

$$BR(\tau^- \to K^-\nu_\tau) = \frac{G_F^2 f_K^2|V_{us}|^2 m_\tau^3\tau_\tau}{16\pi\hbar}\left(1-\frac{m_K^2}{m_\tau^2}\right)^2 S_{EW},$$

Table 2: The current status of the branching fraction for the strange τ decays.

Decay Mode	Branching Fraction (%)	BELLE	*BABAR*
$BR(\tau \to K\nu_\tau)$	0.697 ± 0.010		[8]
$BR(\tau^- \to K^-\pi^0\nu_\tau)$	0.431 ± 0.015		[1]
$BR(\tau^- \to K^-\pi^0\pi^0\nu_\tau\ (ex.\ K^0))$	0.060 ± 0.022		
$BR(\tau^- \to K^-\pi^0\pi^0\pi^0\nu_\tau\ (ex.\ K^0,\eta))$	0.039 ± 0.022		
$BR(\tau^- \to K^0\pi^-\nu_\tau)$	0.831 ± 0.018	[3]	[2]
$BR(\tau^- \to K^0\pi^-\pi^0\nu_\tau)$	0.350 ± 0.015		[17]
$BR(\tau^- \to K^0\pi^-\pi^0\pi^0\nu_\tau)$	0.031 ± 0.023		
$BR(\tau^- \to K^0h^-h^-h^+\nu_\tau)$	0.029 ± 0.020		
$BR(\tau^- \to K^-\pi^-\pi^+\nu_\tau\ (ex.\ K^0))$	0.294 ± 0.007	[4]	[5]
$BR(\tau^- \to K^-\pi^-\pi^+\pi^0\nu_\tau\ (ex.\ K^0,\eta))$	0.078 ± 0.012		
$BR(\tau^- \to K^-\eta\nu_\tau)$	0.016 ± 0.001	[7]	
$BR(\tau^- \to K^-\eta\pi^0\nu_\tau)$	0.005 ± 0.001	[7]	
$BR(\tau^- \to K^0\eta\pi^-\nu_\tau)$	0.009 ± 0.001	[7]	
$BR(\tau^- \to K^-K^-K^+\nu_\tau)$	0.0024 ± 0.0008	[4]	[5]
$BR(\tau^- \to K^-K^0K^0\nu_\tau)$ from $\tau^- \to K^-K^-K^+\nu_\tau \times \frac{\phi\to K^0K^0}{\phi\to K^-K^+}$	0.0015 ± 0.0001		
Total	$2.91(55) \pm 0.05(10)$		
Branching Fractions from HFAG constrained fit [18] χ^2/d.o.f.=135.2/115 CL=9.6%			

Using the kaon decay constant $f_K = 157 \pm 2\,\text{MeV}$ [12], and $S_{EW} = 1.0201 \pm 0.0003$ [19], *BABAR* determined $|V_{us}| = 0.2193 \pm 0.0032$. This method has a theoretical uncertainty of 1.27%.

Figure 1 shows a summary of $|V_{us}|$ measurements, including the HFAG values of $|V_{us}|$ for the three methods mentioned above.

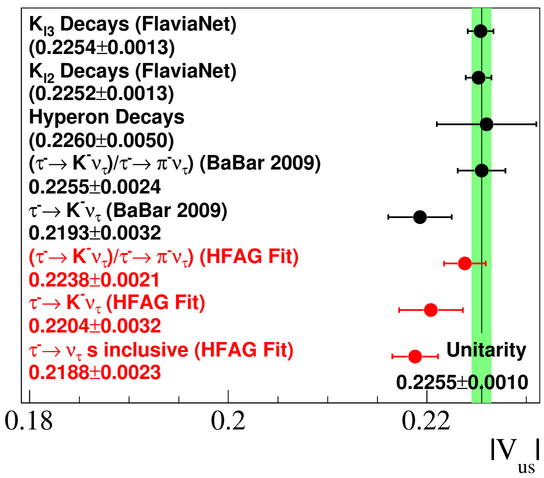

Figure 1: A summary of $|V_{us}|$ measurements. The FlaviaNet measurements come from [10], the hyperon decays come from [20], the *BABAR* τ measurements come from [8] and the HFAG results come from [18].

3. Charged Lepton Universality

Charged lepton universality $\mu - e$ can be tested using

$$\left(\frac{g_\mu}{g_e}\right)^2_\tau = \frac{BR(\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau)}{BR(\tau^- \to e^- \overline{\nu}_e \nu_\tau)} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)},$$

where $f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x$, assuming that the neutrino masses are negligible [21]. The *BABAR* paper [8] gives $\left(\frac{g_\mu}{g_e}\right)_\tau = 1.0036 \pm 0.0020$, yielding a new world average from τ decays of 1.0018 ± 0.0014 [18]. Figure 2 shows the current status of $\mu - e$ lepton universality.

τ-μ universality is tested with

$$\left(\frac{g_\tau}{g_\mu}\right)^2_h = \frac{BR(\tau \to h\nu_\tau)}{BR(h \to \mu\nu_\mu)} \frac{2m_h m_\mu^2 \tau_h}{(1+\delta_h) m_\tau^3 \tau_\tau} \left(\frac{1 - m_\mu^2/m_h^2}{1 - m_h^2/m_\tau^2}\right)^2,$$

where the radiative corrections are $\delta_\pi = (0.16 \pm 0.14)\%$ and $\delta_K = (0.90 \pm 0.22)\%$ [15]. *BABAR* [8] determined $\left(\frac{g_\tau}{g_\mu}\right)_{\pi(K)} = 0.9856 \pm 0.0057$ (0.9827 ± 0.0086) and $\left(\frac{g_\tau}{g_\mu}\right)_h = 0.9850 \pm 0.0054$, where the world averaged mass, lifetime values and meson decay rates were taken from [22]. A summary of τ-μ universality tests are shown in Figure 2. It is interesting to note, that the measurements of $\left(\frac{g_\tau}{g_\mu}\right)_h$ for both kaon and pions are low compared to the HFAG values from the constrained fit and Standard Model expectation.

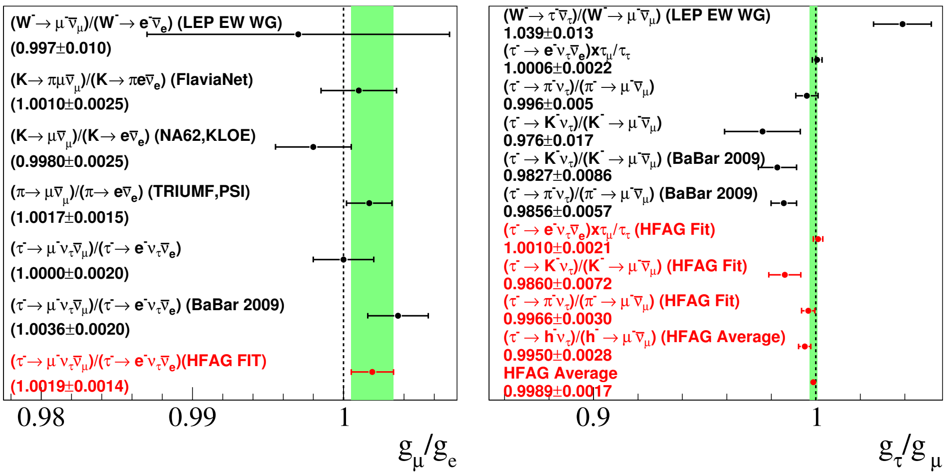

Figure 2: (left) The current status of g_μ/g_e lepton universality measurements. The HFAG average is the weighted average of previous τ results with the recent *BABAR* g_μ/g_e measurement. (right) The current status of g_τ/g_μ lepton universality measurements. The HFAG values are presented for: g_τ/g_μ determined from $\Gamma(\tau^- \to e^-\nu_\tau\bar{\nu}_e) \times \tau_\mu/\tau_\tau$ using the HFAG fit for $\tau^- \to e^-\nu_\tau\bar{\nu}_e$; $(g_\tau/g_\mu)_\pi$ using the HFAG fit value for $\tau^- \to \pi^-\nu_\tau$; $(g_\tau/g_\mu)_K$ using the HFAG fit value for $\tau^- \to K^-\nu_\tau$; the average of the HFAG $(g_\tau/g_\mu)_h$ values; and the HFAG average for τ decays.

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