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Measurements of $|V_{us}|$ from τ Decays

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τ decays provide an opportunity to probe the charged weak interaction of both the relative coupling strength to the first and second generation of quarks, the Cabibbo-Kobayashi-Maskawa matrix (CKM) element $|V_{us}|$, as well as the coupling strength to the lepton (g_e, g_μ and g_τ). Many new physics scenarios couple primarily to the third generation, thus any deviation between weak interactions in τ decays and kaon decays could be an indication of new physics. In this paper, we present the recent measurements of hadronic τ decays from Belle, *BABAR* and the improvements in the determination of $|V_{us}|$ from τ decays and tests of Charged Lepton Universality.

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1. Motivation

In the Standard Model, the interaction of the charged weak current with the quarks is described with a single gauge coupling and a unitary transform matrix ($|V_{us}|$), the Cabibbo-Kobayashi-Maskawa matrix (CKM) [1], which results from the mass and weak eigenstates of the quarks not being equivalent:

$$-\frac{g}{\sqrt{2}}\left[\bar{u}_i\gamma^\mu\frac{1-\gamma^5}{2}V_{ij}d_j+\bar{\nu}_i\gamma^\mu\frac{1-\gamma^5}{2}l_i\right]W_\mu^+ + higher\ order\ terms,$$

where $g = g_f = g_e = g_\mu = g_\tau$ is the signal gauge coupling, u_i and d_i represents the up down like quark states, l_i and ν_i represents the charged lepton and neutrino states of the ith generation and $\frac{1-\gamma^5}{2}$ forces the interaction to be left handed. The equality between the gauge couplings for the three generations of leptons is referred to as Charged Lepton Universality. For the first row of the CKM matrix, the unitarity constraint may be written as

$$V_{ud}+V_{us}+V_{ub}=1,$$

where the value of $|V_{ud}|$ used in this comparison is provided from nuclear beta decays [2], the contribution from $|V_{ub}|$ is negligible[3] and $|V_{us}|$ comes from kaon decay measurements[4]. However, hadronic τ decays provide a complimentary method for extracting $|V_{us}|$. This is of particular interest since there are many new physics scenarios that couple primarily to the third generation and could cause a deviation between measurements of $|V_{us}|$ in the kaon and τ systems[5, 6, 7, 8, 9].

1.1 $|V_{us}|$ in τ Decays

In τ decays, there are four main techniques that can be used to extract $|V_{us}|$. In this paper we will discuss the three methods that have been used at the B-Factories. These techniques only require input from τ decays. A description of the fourth method which combines measurements from $\tau \to K\pi\nu$ decays and $K \to \pi l\nu$ decays can be found in [10]. Out of the τ only techniques, the method that has the smallest theoretical limitations comes from the flavor breaking difference with Finite Energy Sum Rules (FESR)[11]. The flavor breaking difference can be written as

$$\frac{R^w_{\tau,strange}}{|V_{us}|^2}-\frac{R^w_{\tau,non-strange}}{|V_{ud}|^2}=\delta R^w_{\tau,SU3\ breaking},$$

where $R_{\tau,strange} = \Gamma(\tau^- \to X_{strange}\nu_\tau)/\Gamma(\tau \to e\nu\overline{\nu})$ is the strange hadronic width, $R_{\tau,non-strange} = \Gamma(\tau^- \to X_{non-strange}\nu_\tau)/\Gamma(\tau \to e\nu\overline{\nu})$ is the non-strange hadronic width and $\delta R_{\tau,SU3\ breaking}$ is the theoretical SU(3) flavor breaking correction which is determined using Operator Product Expansion (OPE). The w represents that this equation holds for any analytic weight. In general, the weights can be constructed to minimize the total uncertainty. However, due to the limited amount of information on the inclusive spectral density functions of the current experimental measurements, the results presented here are un-weighted. The weighted inclusive strange and non-strange spectral density functions are constructed from the desired analytic weight, the sum of invariant mass distributions for each of the strange and non-strange decay modes and normalized to the corresponding branching fractions. Experimentally, this is challenging due to the number of channels that need to be measured. Moreover, since there are no solid predictions for the branching fractions of hadronic individual τ decays, all possible modes must be measured or have an upper bound placed on them. This technique has completely orthogonal theoretical and experimental uncertainties to the kaon measurements. If all of the branching fractions and spectral functions are updated with the data from the Belle and BABAR, this method would be expected to make the most precise measurement of $|V_{us}|$ [11].

The most precise technique for determining $|V_{us}|$ from τ decays is currently from the branching ratio:

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

where $f_K/f_\pi = 1.1936 \pm 0.0053$ [12, 13, 14, 15] is determined from Lattice QCD, $|V_{ud}|$ [2], and the long-distance correction $\delta_{LD} = (0.03 \pm 0.44)\%$ is estimated [16] using corrections to $\tau \to h\nu_\tau$ and $h \to \mu\nu_\mu$ [17, 18]. This method is analogous to the method used in K_{l2} decays and therefore has the same Lattice QCD uncertainties.

$|V_{us}|$ can be directly extracted from the measurement of the branching fraction $\tau^- \to K^-\nu_\tau$,

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

where the kaon decay constant is $f_K = 156.1 \pm 1.1 MeV$ [12, 13, 14, 15] and the electroweak correction is $S_{EW} = 1.0201 \pm 0.0003$ [19]. In contrast to the latter method, this method is sensitive to the absolute normalization, however by construction, it is also affected by Lattice QCD uncertainties.

1.2 Charged Lepton Universality and τ Decays.

There are numerous techniques for testing Charged Lepton Universality in τ decays. We will limit the techniques to those used at BABAR and Belle. The ratio of branching fractions $\mathscr{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$ and $\mathscr{B}(\tau^- \to e^-\overline{\nu}_e\nu_\tau)$ can be used to test Charged Lepton Universality between electrons and muons.

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

where $f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x$, assuming that the neutrino masses are negligible [20]. Charged Lepton Universality between the τ and μ leptons can be tested with

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

where the radiative corrections are $\delta_\pi = (0.16 \pm 0.14)\%$ and $\delta_K = (0.90 \pm 0.22)\%$ [17, 21, 22]. The world average mass, lifetime values and meson decay rates were taken from [23].

2. Detectors

The Belle and *BABAR* detectors are located on e^+e^- accelerators at KEK and SLAC respectively. The centre of mass energy recorded by these experiments is at or near $10.58 GeV$. The *BABAR* detector has collected $531 fb^{-1}$ of data, while the Belle experiment has collected $1 ab^{-1}$ data. At these energies, the cross-section for $e^+e- \to \tau^+\tau^-$ production is $(0.919 \pm 0.003)nb$ which corresponds to having recorded $\mathcal{O}(5-10\times 10^8)$ τ-pairs. The exact luminosity used is analysis dependent. A detailed description of the *BABAR* and Belle detectors can be found at [24] and [25].

At *BABAR* and Belle, τ-pair events are simulated with higher-order radiative corrections using the KK2f Monte Carlo (MC) generator [26] with τ decays simulated with Tauola[27]. The final-state-radiation in the τ decays is simulated in Tauola using Photos[28]. In Belle, the detector response is simulated using GEANT3[29], while *BABAR* used GEANT4[30].

3. Experimental Results

The *BABAR* and Belle experiments, have measured a large fraction of the branching fractions for the hadronic τ decay[3]. This includes the majority of the main strange τ branching fractions and upper limits on the unmeasured strange decay modes[31, 32]. Table 1 presents a summary of the strange branching fraction measurements as well as the upper limits on unmeasured strange decay from the Belle and *BABAR* experiments. These are of particular importance since it is these decay modes that limit the extraction of $|V_{us}|$. However, to measure many of the strange decay modes, it requires simultaneous measurements of the non-strange decay modes. A complete list of the measured decay modes from the B-Factories can be found at [3].

In contrast to the branching fractions, there are only a small number of measured invariant mass spectra[33, 34, 35, 36, 37, 38]. Depending on the analysis at Belle or *BABAR* the invariant mass spectra have been analyzed using a fit[36, 37, 38] or unfolded[33, 34, 35] to allow for their use in determining the spectral moments. The two main strange decay channels that have been measured by the B-factories are the $\tau^- \to K^0_S\pi^-\nu_\tau$, and $\tau^- \to K^-\pi^-\pi^+\nu$.

4. Discussion and Conclusion

The extraction of $|V_{us}|$ from the B-Factories results is computed by HFAG using the fitted HFAG branching fractions. The HFAG values of $|V_{us}|$ compared to the kaon measurements are presented in Figure 1. In contrast to the kaon measurements, the uncertainties on all of the $|V_{us}|$ measurements extracted from τ decays are limited by the experimental uncertainties. From Figure 1, it can be seen that the B-Factory measurements of $|V_{us}|$ extracted from ratio of $\frac{\mathcal{B}(\tau\to K\nu)}{\mathcal{B}(\tau\to\pi\nu)}$ and directly from $\mathcal{B}(\tau \to K\nu)$ are consistent with unitarity determined from[2]. These measurements are dominated by the *BABAR* measurement [39]. Interestingly, the value of $|V_{us}|$ extracted using the FESR method has a deviation from unitarity of 3.4σ. With the recent upper-limits on the unmeasured τ decay modes, the possibility of this deviation resulting from missing decay modes is becoming smaller. Moreover, although the measurements of the hadronic τ decays at Belle and *BABAR* seem to be systematically lower than the previous world averages, the sum of the branching ratios is consistent with unity. The deviation in the FESR approach for $|V_{us}|$ and the systematically

Table 1: The current status of the branching fraction for the strange τ decays.

Decay Mode	Branching Fraction (%)	Belle	BABAR
$\mathscr{B}(\tau \to K\nu)$	0.6955 ± 0.0096		[39]
$\mathscr{B}(\tau^- \to K^-\pi^0\nu_\tau)$	0.4322 ± 0.0149		[40]
$\mathscr{B}(\tau^- \to K^-\pi^0\pi^0\nu_\tau\ (ex.\ K^0))$	0.0630 ± 0.0222		
$\mathscr{B}(\tau^- \to K^-\pi^0\pi^0\pi^0\nu_\tau\ (ex.\ K^0,\eta))$	0.0419 ± 0.0218		
$\mathscr{B}(\tau^- \to K^0\pi^-\nu_\tau)$	0.8206 ± 0.0182	[36]	[41]
$\mathscr{B}(\tau^- \to K^0\pi^-\pi^0\nu_\tau)$	0.3649 ± 0.0108	[42]	[38]
$\mathscr{B}(\tau^- \to K^0\pi^-\pi^0\pi^0\nu_\tau)$	0.0269 ± 0.0230		
$\mathscr{B}(\tau^- \to K^0h^-h^-h^+\nu_\tau)$	0.0222 ± 0.0202		
$\mathscr{B}(\tau^- \to K^-\pi^-\pi^+\nu_\tau\ (ex.\ K^0))$	0.2923 ± 0.0068	[33]	[43]
$\mathscr{B}(\tau^- \to K^-\pi^-\pi^+\pi^0\nu_\tau\ (ex.\ K^0,\eta))$	0.0411 ± 0.0143		
$\mathscr{B}(\tau^- \to K^-\eta\nu_\tau)$	0.0153 ± 0.0008	[44]	[45]
$\mathscr{B}(\tau^- \to K^-\eta\pi^0\nu_\tau)$	0.0048 ± 0.0012	[44]	
$\mathscr{B}(\tau^- \to K^0\eta\pi^-\nu_\tau)$	0.0094 ± 0.0015	[44]	
$\mathscr{B}(\tau^- \to K^-\omega\nu_\tau)$	0.0410 ± 0.0092		
$\mathscr{B}(\tau^- \to K^-\phi\nu_\tau(\phi \to K^-K^+))$	0.0037 ± 0.0014	[33]	[43]
Total	$2.87(46) \pm 0.04(98)$		
Branching Fractions from HFAG fit [3] χ^2/d.o.f.=143.5/118 CL=5.5%			

low branching ratios could be related to the difference in the definitions of the decay modes between the B-Factories and previous experiments especially given that the π^0 branching ratios tend not to be measured at the BABAR and Belle. On the theoretical side, the current weights used for the calculation of $|V_{us}|$ have been shown to have potential problems with convergence [11, 46, 47] which are not included in the theoretical uncertainties. Unfortunately, the limited information on the strange spectral density function prevents the use of more sophisticated weights which are not known to have problems with convergence. Therefore, it would be prudent to wait for future results before drawing conclusions on the meaning of the deviation.

The analysis in [39], also used the leptonic τ decays and the $\tau^- \to h^-\nu_\tau$ to test Charged Lepton Universality. Figures 2 and 3 present a comparison of the BABAR Charged Lepton Universality measurements to previous experiments. The BABAR measurements were consistent with the assumption of Charge Lepton Universality. It has been suggested that the small deviations in the g_τ/g_μ from comparing $\tau^- \to h^-\nu_\tau$ to $h^- \to \mu^-\bar{\nu_\mu}$ could be related to the radiative corrections used in the analysis [17, 21, 22].

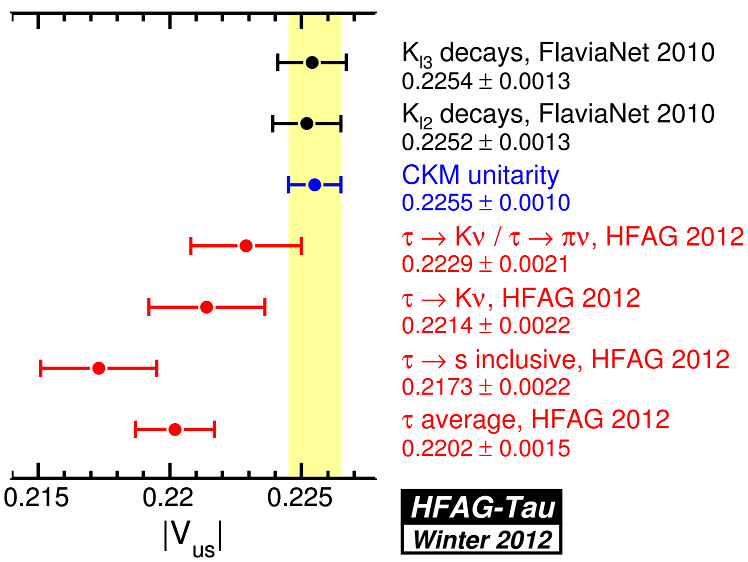

Figure 1: An update of $|V_{us}|$ from the HFAG 2012 report[3] for the hadronic τ decays. The HFAG values of $|V_{us}|$ are extracted using the average branching fractions from HFAG. The three upper values are from K_{l3} decays [4], K_{l2} decays [4] and the unitarity constraint [2].

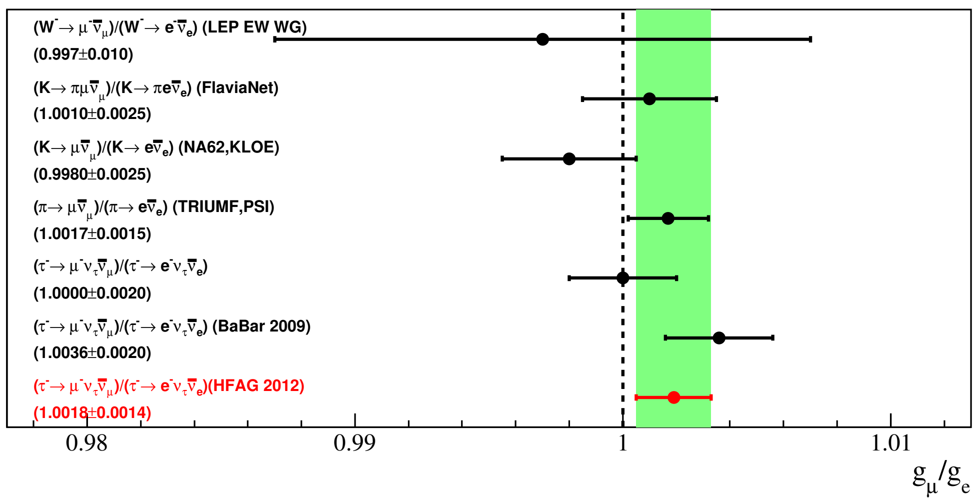

Figure 2: The current status of g_μ/g_e lepton universality measurements. The *BABAR* measurement is from [39], while the HFAG values are from[3]. The HFAG average [3] is the weighted average of previous τ results with the recent *BABAR* g_μ/g_e measurement. The τ measurements from before *BABAR* are from [23]. The other measurements are taken from [48, 3].

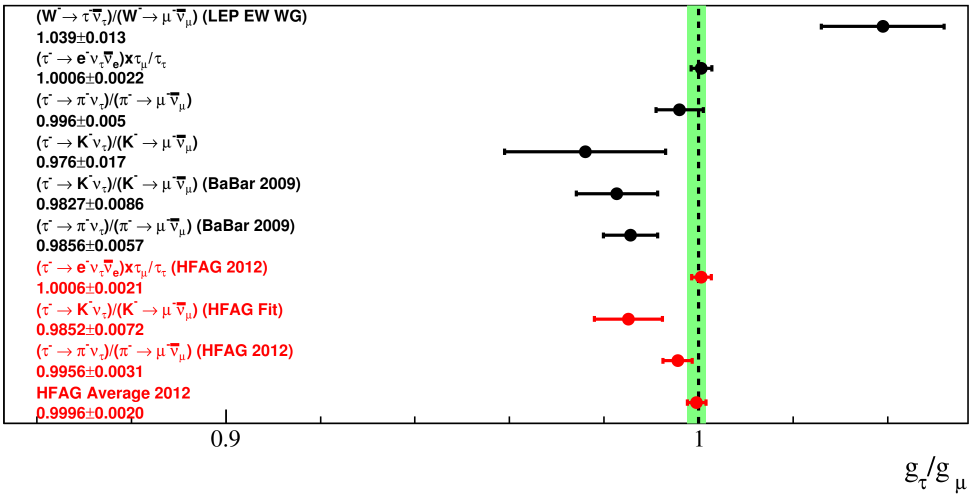

Figure 3: The current status of g_τ/g_μ lepton universality measurements. The *BABAR* measurements are from [39], while the HFAG values are from[3]. The HFAG average [3] is the weighted average of previous τ results with the recent *BABAR* g_μ/g_e measurement. The τ measurements from before *BABAR* are from [23]. The other measurements are taken from [48, 3].

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