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Measurement of $|V_{us}|$ using hadronic tau decays from *BABAR* & Belle

Swagato Banerjee[*†]
University of Victoria, P.O. Box 3055, Victoria, B.C., CANADA V8W 3P6.
E-mail: swaban@slac.stanford.edu

We report on measurements of branching fractions for several hadronic tau decays to final states with kaons, which can be used to determine the strange quark mass and the element $|V_{us}|$ of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix. The results are obtained from data collected with the *BABAR* and Belle detectors at the PEP-II and KEKB asymmetric-energy e^+e^- colliders at SLAC and KEK, respectively, both operating at center-of-mass energies near the $\Upsilon(4S)$ resonance.

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[*]Speaker.
[†]For *BABAR* & Belle collaborations.

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1. Introduction

The weak interaction universality between quarks was asserted by Cabibbo with the introduction of a mixing angle between the £rst and second quark generations [1]. Three-generation quark mixing between the mass eigenstates and the ¤avor eigenstates is described by the unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix [2].

The magnitude of the largest off-diagonal element of this CKM matrix, $|V_{us}|$, has historically been measured from three-body kaon ($K\ell3$) and hyperon decays [3,4]. $|V_{us}|$ has also been extracted from a comparison of the radiative inclusive rates of two-body kaon ($K\ell2$) and pion decays, along with lattice-QCD results of the meson decay constants [5]. Recently, the analysis of ¤avor-breaking sum rules has shown that inclusive measurements of the strange spectral function, obtained from hadronic τ decays having net strangeness of unity in the £nal state, can provide a direct determination of $|V_{us}|$ and the strange quark mass, m_s [6–12].

Present generation B factories, *BABAR* and Belle, also serve as τ factories thanks to the large τ pair production cross-section $\sigma_{e^+e^-\to\tau^+\tau^-} = 0.919 \pm 0.003\,\mathrm{nb}$ [13], as determined using the `KK2f` Monte Carlo (MC) generator [14] at a center-of-mass (CM) energy of $\sqrt{s}$ = 10.58 GeV. Using the world's largest sample of hadronic τ decays collected with the *BABAR* and Belle detectors at the PEP-II and KEKB asymmetric-energy e^+e^- colliders, measurement of m_s and $|V_{us}|$ can be performed with unprecedented precision [16,17].

Study of the strange spectral function from these τ data is still in progress. However, using the updated knowledge of $m_s(2\,\mathrm{GeV}) = 94 \pm 6\,\mathrm{MeV}/c^2$ from lattice calculations [18], $|V_{us}|$ can be extracted with relatively small theoretical uncertainties [15,16,19], using available measurements of branching fractions of all τ decays into £nal states containing an odd number of kaons.

2. Hadronic τ decays

Here we report on the recent *BABAR* [20,21] and Belle [22] measurements:

$$\begin{aligned}
\mathscr{B}(\tau^- \to K^-\pi^0\nu_\tau) &= (0.416 \pm 0.003 \pm 0.018)\%\ [20],\\
\mathscr{B}(\tau^- \to \pi^-\pi^-\pi^+\nu_\tau) &= (8.83 \pm 0.01 \pm 0.13)\%\ [21],\\
\mathscr{B}(\tau^- \to K^-\pi^-\pi^+\nu_\tau) &= (0.273 \pm 0.002 \pm 0.009)\%\ [21],\\
\mathscr{B}(\tau^- \to K^-\pi^-K^+\nu_\tau) &= (0.1346 \pm 0.0010 \pm 0.0036)\%\ [21],\\
\mathscr{B}(\tau^- \to K^-K^-K^+\nu_\tau) &= (1.58 \pm 0.13 \pm 0.12) \times 10^{-5}\ [21] \text{ and}\\
\mathscr{B}(\tau^- \to K^0_S\pi^-\nu_\tau) &= (0.404 \pm 0.002 \pm 0.013)\%\ [22],
\end{aligned}$$

where the uncertainties are statistical and systematic, respectively, and the charge-conjugate modes are implied. These results are more precise than the previously published measurements [23].

The vector $K^\star(892)^-$ resonance is expected to nearly saturate the $(K\pi)^-$ £nal state. The Belle analysis of the $K^0_S\pi^-$ invariant mass spectrum reveals contributions from the vector $K^\star(892)^-$ resonance as well as other states [22]. For the £rst time, the $K^\star(892)^-$ mass and width have been measured in τ decays: $m(K^\star(892)) = (895.47 \pm 0.20(stat) \pm 0.44(syst) \pm 0.59(mod))\,\mathrm{MeV}/c^2$, $\Gamma(K^\star(892)) = (46.2 \pm 0.6(stat) \pm 1.0(syst) \pm 0.7(mod))\,\mathrm{MeV}$. The $K^\star(892)^-$ mass is signi£cantly different from the current world-average value of $891.66 \pm 0.26\,\mathrm{MeV}/c^2$ [23].

We also report on the £rst measurement of $\mathscr{B}(\tau^- \to \phi K^- \nu_\tau) = (4.05 \pm 0.25 \pm 0.26) \times 10^{-5}$ by the Belle experiment [24], which is consistent with the new *BABAR* measurement of $\mathscr{B}(\tau^- \to \phi K^- \nu_\tau) = (3.39 \pm 0.20 \pm 0.28) \times 10^{-5}$, and show that the $\tau^- \to \phi K^- \nu_\tau$ decay saturates the $K^- K^- K^+$ £nal state [21]. The £rst measurement of $\mathscr{B}(\tau^- \to \phi \pi^- \nu_\tau) = (3.42 \pm 0.55 \pm 0.25) \times 10^{-5}$ has been performed by the *BABAR* experiment [21], which provides an interesting laboratory to study OZI suppression [25], because the $\tau^- \to \phi K^- \nu_\tau$ decay, with a comparable rate, is not OZI suppressed.

3. $|V_{us}|$ from τ decays

The hadronic width of the τ is normalized as: $R_\tau = \Gamma[\tau^- \to \text{hadrons}^- \nu_\tau(\gamma)]/\Gamma[\tau^- \to e^- \bar{\nu}_e \nu_\tau(\gamma)]$. The spectral moments are de£ned as: $R_\tau^{kl} = \int_0^1 dz(1-z)^k z^l \frac{dR_\tau}{dz}$, where $z = \frac{q^2}{m_\tau^2}$ is the square of the scaled invariant mass of the hadronic system. The ¤avor-breaking term $\delta R_\tau^{kl} = \frac{R^{kl}_{\tau,\text{non-strange}}}{|V_{ud}|^2} - \frac{R^{kl}_{\tau,\text{strange}}}{|V_{us}|^2}$ is sensitive to m_s. This term for the $kl = 00$ moment has the smallest theoretical uncertainty (given in parentheses): $\delta R^{00}_{\tau,th} = 0.1544(37) + 9.3(3.4) m_s^2 + 0.0034(28) = 0.240(32)$ [16,18].

We can then measure $|V_{us}| = \sqrt{R^{00}_{\tau,\text{strange}} / \left[\frac{R^{00}_{\tau,\text{non-strange}}}{|V_{ud}|^2} - \delta R^{00}_{\tau,th}\right]}$ from the measured τ branching fraction into strange £nal states, where we use $|V_{ud}| = 0.97377 \pm 0.00027$ [23]. The modest 13% error on $\delta R^{00}_{\tau,th}$ gives a relatively small contribution to the error on $|V_{us}|$ [19].

Here, we use the values of τ branching fractions as estimated in Reference [15]. The electronic branching fraction $\mathscr{B}_e^{\text{uni}} = (17.818 \pm 0.032)\%$ is obtained by averaging the direct measurements of the electronic and muonic branching fractions and the lifetime of the τ lepton. Using lepton universality, the total hadronic τ branching fraction is $\mathscr{B}_{\text{had}} = 1 - 1.97257 \mathscr{B}_e^{\text{uni}} = (64.853 \pm 0.063)\%$, and the total τ hadronic width is $R_\tau = 3.640 \pm 0.010$. The non-strange width is $R_{\text{non-strange}} = R_\tau - R_{\text{strange}}$, where the branching fractions into strange £nal states are listed in Table 1.

The results for the $K^-\pi^0$, $K^-\pi^+\pi^-$ and $\bar{K}^0\pi^-$ branching fractions in [15] have been averaged with the results presented here [20–22], where the errors include a scale factor S following the PDG prescription [23]. The total branching fraction into strange £nal states has also been calculated by replacing $\mathscr{B}(\tau^- \to K^- \nu_\tau)$ with $(7.15 \pm 0.03) \times 10^{-3}$, obtained from theoretical predictions using the much better known $K^- \to \mu^- \nu_\mu(\gamma)$ decay rate and assuming τ-μ universality.

The updated value is $|V_{us}| = 0.2157 \pm 0.0031$ using measured τ branching fractions alone, and $|V_{us}| = 0.2171 \pm 0.0030$ using the predicted $\tau^- \to K^- \nu_\tau$ branching fraction as well. The uncertainties are dominated by the $\sim 2\%$ experimental errors on the measurements of the τ branching fractions. Some of the uncertainties have been reduced almost by a factor of two, because of the new *BABAR* and Belle results. In the near future, we expect to reduce the uncertainty on the strange branching fractions by an additional factor of two, corresponding to a precision of 0.7% on $|V_{us}|$.

4. Summary

In Figure 1, updated estimates of $|V_{us}|$ from τ decays are compared with those extracted from $K\ell3$ [26], $K\ell2$ [27] and hyperon decays [28]. The values obtained from τ decays with and without the predicted $\tau^- \to K^- \nu_\tau$ branching fraction are lower than the estimate of $|V_{us}| = 0.2275 \pm 0.0012$ obtained by using the unitarity constraint from the value of $|V_{ud}|$, mentioned above, by 3.2σ and

Table 1: τ branching fractions into strange £nal states from [15], averaged with results from [20–22] along a scale factor S following the PDG prescription [23], sum up to $(28.44 \pm 0.74) \times 10^{-3}$ as shown in this table. If the $\mathscr{B}(\tau^- \to K^- \nu)$ is replaced with $(7.15 \pm 0.03) \times 10^{-3}$, the sum becomes $(28.78 \pm 0.71) \times 10^{-3}$.

Mode	$\mathscr{B}(10^{-3})$ [15]	Updated $\mathscr{B}(10^{-3})$ with results from [20–22]
K^-	6.81 ± 0.23	
$K^-\pi^0$	4.54 ± 0.30	Average with $4.16 \pm 0.18 \Rightarrow 4.26 \pm 0.16$ $(S = 1.0)$
$\bar{K}^0\pi^-$	8.78 ± 0.38	Average with $8.08 \pm 0.26 \Rightarrow 8.31 \pm 0.28$ $(S = 1.3)$
$K^-\pi^0\pi^0$	0.58 ± 0.24	
$\bar{K}^0\pi^-\pi^0$	3.60 ± 0.40	
$K^-\pi^+\pi^-$	3.30 ± 0.28	Average with $2.73 \pm 0.09 \Rightarrow 2.80 \pm 0.16$ $(S = 1.9)$
$K^-\eta$	0.27 ± 0.06	
$(\bar{K}3\pi)^-$ (estimated)	0.74 ± 0.30	
$K_1(1270)^- \to K^-\omega$	0.67 ± 0.21	
$(\bar{K}4\pi)^-$ (estimated) and $K^{*-}\eta$	0.40 ± 0.12	
Sum	29.69 ± 0.86	Updated Estimate: 28.44 ± 0.74

3.5σ, respectively. Possible implications for new physics due to this departure from the unitarity constraint are discussed in Reference [29].

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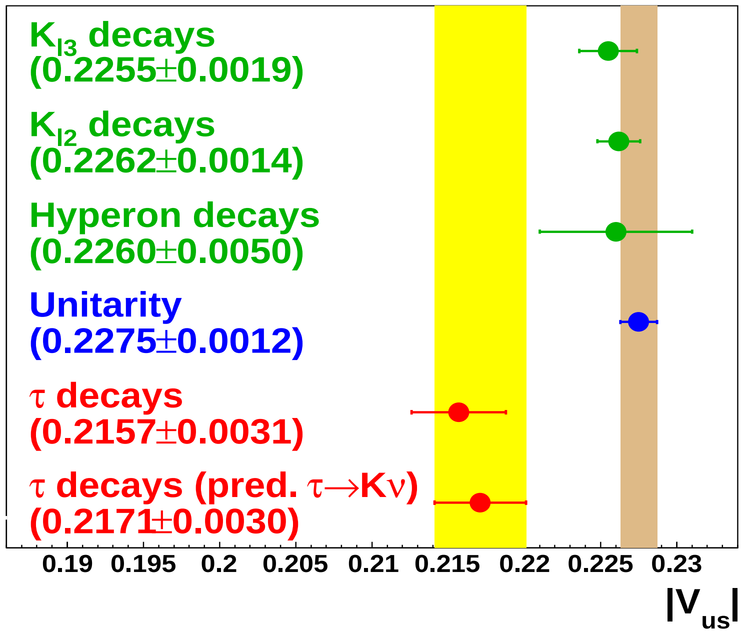
Figure 1: Comparison of different estimates of $|V_{us}|$.



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