Measurement of $|V_{us}|$ using hadronic tau decays from $\text{BaBar} & \text{Belle}$

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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 $\text{BaBar}$ 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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1. Introduction

The weak interaction universality between quarks was asserted by Cabibbo with the introduction of a mixing angle between the first and second quark generations [1]. Three-generation quark mixing between the mass eigenstates and the flavor 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 ($K\ell\bar{3}$) and hyperon decays [3,4]. $|V_{us}|$ has also been extracted from a comparison of the radiative inclusive rates of two-body kaon ($K\ell\bar{2}$) and pion decays, along with lattice-QCD results of the meson decay constants [5]. Recently, the analysis of flavor-breaking sum rules has shown that inclusive measurements of the strange spectral function, obtained from hadronic $\tau$ decays having net strangeness of unity in the final 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 $\tau$ factories thanks to the large $\tau$ pair production cross-section $\sigma_{e^+e^-\rightarrow\tau^+\tau^-} = 0.919 \pm 0.003 \text{nb}$ [13], as determined using the $K\bar{K}2\ell$ 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 $\tau$ 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 $\tau$ data is still in progress. However, using the updated knowledge of $m_s(2\text{GeV}) = 94 \pm 6$ 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 $\tau$ decays into final states containing an odd number of kaons.

2. Hadronic $\tau$ decays

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

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

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 $K^*(892)^-\tau$ resonance is expected to nearly saturate the $(K\pi)^-\tau$ final state. The Belle analysis of the $K^0\pi^-\tau$ invariant mass spectrum reveals contributions from the vector $K^*(892)^-\tau$ resonance as well as other states [22]. For the first time, the $K^*(892)^-$ mass and width have been measured in $\tau$ decays: $m(K^*(892)) = (895.47 \pm 0.20(stat) \pm 0.44(syst) \pm 0.59(mod))\text{MeV}/c^2$, $\Gamma(K^*(892)) = (46.2 \pm 0.6(stat) \pm 1.0(syst) \pm 0.7(mod))\text{MeV}$. The $K^*(892)^-$ mass is significantly different from the current world-average value of $891.66 \pm 0.26$ MeV/$c^2$ [23].
We also report on the first measurement of $\mathcal{B}(\tau^- \to \phi K^+ \nu_\tau) = (4.05 \pm 0.25 \pm 0.26) \times 10^{-5}$ by the Belle experiment [24], which is consistent with the new Babar measurement of $\mathcal{B}(\tau^- \to \phi K^- \nu_\tau) = (3.39 \pm 0.20 \pm 0.28) \times 10^{-5}$, and show that the $\tau^- \to \phi K^- \nu_\tau$ decay saturates the $K^- K^+ K^+$ final state [21]. The first measurement of $\mathcal{B}(\tau^- \to \phi \pi^- \nu_\tau) = (3.42 \pm 0.55 \pm 0.25) \times 10^{-5}$ 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 \(\tau\) decays

The hadronic width of the \(\tau\) 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 defined as: $R_{\tau|kl}^k = \int_0^1 dz (1-z)^k \frac{dR_\tau}{dz}$, where $z = \frac{m_\tau^2}{m_\tau^2}$ is the square of the scaled invariant mass of the hadronic system. The flavor-breaking term $\delta R_{\tau|kl}^{g} = \frac{R_{\tau|kl}^{g_{\text{non-}}-\text{strange}} - R_{\tau|kl}^{g_{\text{strange}}}}{|V_{ud}|^2}$ is sensitive to $m_\tau$. This term for the $kl = 00$ moment has the smallest theoretical uncertainty (given in parentheses): $\delta R_{\tau|00|kl} = 0.1544(37) + 9.3(3.4)m_\tau^2 + 0.0034(28) = 0.240(32)$ [16,18].

We can then measure $|V_{us}| = \sqrt{R_{\tau|00|kl}^0 / \left[ R_{\tau|00|kl}^{g_{\text{non-}}-\text{strange}} - \delta R_{\tau|00|kl}^{g_{\text{strange}}} \right]}$ from the measured $\tau$ branching fraction into strange final states, where we use $|V_{us}| = 0.97377 \pm 0.00027$ [23]. The modest 13% error on $\delta R_{\tau|00|kl}$ gives a relatively small contribution to the error on $|V_{us}|$ [19].

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

The results for the $K^- \pi^0$, $K^- \pi^+ \pi^-$ and $K^0 \tau^- \pi^+$ 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 final states has also been calculated by replacing $\mathcal{B}(\tau^- \to K^- \nu_\tau)$ 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 $\tau$-$\mu$ universality.

The updated value is $|V_{us}| = 0.2157 \pm 0.0031$ using measured $\tau$ 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 $\tau$ 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 I, updated estimates of $|V_{us}|$ from $\tau$ decays are compared with those extracted from $K^0 \ell 3$ [26], $K^0 \ell 2$ [27] and hyperon decays [28]. The values obtained from $\tau$ 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 $3.2\sigma$ and
Table 1: \( \tau \) branching fractions into strange final 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 \( \mathcal{B}(\tau^- \to K^- \nu) \) is replaced with \( (7.15 \pm 0.03) \times 10^{-3} \), the sum becomes \( (28.78 \pm 0.71) \times 10^{-3} \).

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

Sum: \( 29.69 \pm 0.86 \) Updated Estimate: \( 28.44 \pm 0.74 \)

3.5\( \sigma \), 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 $|V_{us}|$.

- $K_{l3}$ decays $(0.2255\pm 0.0019)$
- $K_{l2}$ decays $(0.2262\pm 0.0014)$
- Hyperon decays $(0.2260\pm 0.0050)$
- Unitarity $(0.2275\pm 0.0012)$
- $\tau$ decays $(0.2157\pm 0.0031)$
- $\tau$ decays (pred. $\tau \rightarrow K\nu$) $(0.2171\pm 0.0030)$

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