Determination of $|V_{us}|$ from $\tau$ Decays

Ian. M. Nugent (representing the B\text{B}A\text{R} Collaboration)
III. Physikalisches Institut
Physikzentrum
RWTH Aachen
52056 Aachen, Germany
Email: inugent@uvic.ca
Proceedings of CKM 2012, the 7th International Workshop on the CKM
Unitarity Triangle, University of Cincinnati, USA, 28 September - 2 October 2012

Abstract

The weak interaction between the first and second generation of quarks, the Cabibbo-Kobayashi-Maskawa matrix (CKM) element $|V_{us}|$, can be probed using hadronic $\tau$ decays. In this paper, we present the recent measurements of hadronic $\tau$ decays from BELLE and B\text{B}A\text{R} and the improvements in the determination of $|V_{us}|$ from $\tau$ decays.

1 Introduction

Hadronic $\tau$ decays provide an opportunity to probe the relation of the first row of the Cabibbo-Kobayashi- Maskawa (CKM) matrix by measuring the coupling of the first and second generation of quarks to the weak charged current, $|V_{us}|$ \cite{1}. Measurements of $|V_{us}|$ from $\tau$ decays are complimentary to the kaon decay measurements\cite{2}. The kaon measurements are consistent with the unitarity condition ($|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$), where the value of $|V_{ud}|$ used in this comparison is provided from nuclear beta decays \cite{3} and the contribution from $|V_{ub}|$ is negligible\cite{4}. However, new physics scenarios that couple primarily to the third generation could cause deviation between measurements of $V_{us}$ in the kaon and $\tau$ systems\cite{5,6,7,8,9}.

In $\tau$ decays, there are multiple techniques that can be used to extract $|V_{us}|$. In this paper, we will limit ourselves to the three most precise methods. The technique that offers the potential for the most precise measurement\cite{10} comes from the flavor breaking difference with Finite Energy Sum Rules (FESR). More specifically,

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

where $R_{\tau,\text{strange}} = \Gamma(\tau^- \to X_{\text{strange}}\nu_\tau)/\Gamma(\tau \to e\nu\bar{\nu})$ is the strange hadronic width, $R_{\tau,\text{non-strange}} = \Gamma(\tau^- \to X_{\text{non-strange}}\nu_\tau)/\Gamma(\tau \to e\nu\bar{\nu})$ is the non-strange hadronic width.
width and $\delta R_{\tau, SU(3)}$ breaking is the theoretical SU(3) flavor breaking correction determined using Operator Product Expansion (OPE). From an experimental perspective, this technique requires that the inclusive strange and non-strange spectral density functions, which are constructed from the sum of invariant mass distributions for each of the strange and non-strange decay modes and normalized to the corresponding branching fractions, are measured. Since there are no solid predictions for the branching fractions of hadronic individual $\tau$ decays, all possible modes must be measured or have an upper bound placed on them. This technique is completely independent of 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 $|V_{us}|$ [10].

Currently, the most precise technique for determining $|V_{us}|$ from tau decays is:

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

where $f_K/f_\pi = 1.1936 \pm 0.0053$ [11] is determined from Lattice QCD, $|V_{ud}|$ [3], and the long-distance correction $\delta_{LD} = (0.03 \pm 0.44)\%$ is estimated [12] using corrections to $\tau \to h\nu_\tau$ and $h \to \mu\nu_\mu$ [13, 14]. This method is analogous to measurements in the kaon system and is sensitive to the same Lattice QCD uncertainties.

Measurements using the absolute branching fraction $\tau^- \to K^-\nu_\tau$,

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

provides a competitive measurement compared to the former techniques, however, it is also sensitive to Lattice QCD uncertainties. For this method, the kaon decay constant is $f_K = 156.1 \pm 1.1 MeV$ [11] and the electroweak correction is $S_{EW} = 1.0201 \pm 0.0003$ [15].

2 Experimental Results

The B-Factories, BABAR and BELLE, have measured many of the branching fractions for the hadronic $\tau$ decay modes [4]. This includes the majority of the main strange $\tau$ branching fractions, which are presented in Table 1 as well as recent limits on unmeasured decay modes [16, 17]. This is in contrast to the small number of measured invariant mass spectra [18, 19, 20].
Table 1: The current status of the branching fraction for the strange $\tau$ decays.

| Decay Mode                                      | Branching Fraction (%) | BELLE     | BaBar     |
|------------------------------------------------|------------------------|-----------|-----------|
| $B(\tau \to K \nu)$                            | 0.6955 ± 0.096         |           |           |
| $B(\tau^- \to K^- \pi^0 \nu_\tau)$            | 0.4322 ± 0.0149        |           |           |
| $B(\tau^- \to K^- \pi^0 \nu_\tau \ (\text{ex. } K^0))$ | 0.0630 ± 0.0222        |           |           |
| $B(\tau^- \to K^- \pi^0 \pi^0 \nu_\tau \ (\text{ex. } K^0, \eta))$ | 0.0419 ± 0.0218        |           |           |
| $B(\tau^- \to K^0 \pi^- \nu_\tau)$            | 0.831 ± 0.018          |           |           |
| $B(\tau^- \to K^0 \pi^- \pi^0 \nu_\tau)$      | 0.3649 ± 0.0108        |           |           |
| $B(\tau^- \to K^0 \pi^- \pi^0 \pi^0 \nu_\tau)$ | 0.0269 ± 0.0230        |           |           |
| $B(\tau^- \to K^0 h^- h^+ \nu_\tau)$           | 0.0222 ± 0.0202        |           |           |
| $B(\tau^- \to K^- \pi^- \pi^+ \nu_\tau \ (\text{ex. } K^0))$ | 0.2923 ± 0.0068        |           |           |
| $B(\tau^- \to K^- \pi^- \pi^+ \pi^0 \nu_\tau \ (\text{ex. } K^0, \eta))$ | 0.0411 ± 0.0143        |           |           |
| $B(\tau^- \to K^- \eta \nu_\tau)$              | 0.0153 ± 0.0008        |           |           |
| $B(\tau^- \to K^- \eta \pi^0 \nu_\tau)$       | 0.0048 ± 0.0012        |           |           |
| $B(\tau^- \to K^0 \eta \pi^- \nu_\tau)$       | 0.0094 ± 0.0015        |           |           |
| $B(\tau^- \to K^- \omega \nu_\tau)$            | 0.0410 ± 0.0092        |           |           |
| $B(\tau^- \to K^- \phi \nu_\tau (\phi \to K^- K^+))$ | 0.0037 ± 0.0014        |           |           |
| **Total**                                        | **2.87(46) ± 0.04(98)**|           |           |

Branching Fractions from HFAG fit $^{[3]}$ $\chi^2$/d.o.f. = 143.5/118 CL = 5.5%.

### 3 Discussion and Conclusion

The HFAG value of $|V_{us}|$ extracted using the three techniques mentioned above are compared to the kaon measurements in Figure 1. In all of these methods, the uncertainty is limited by the experimental precision. Both of the measurements of $V_{us}$ extracted from ratio of $\frac{B(\tau \to K \nu)}{B(\tau \to \pi \nu)}$ and directly from $B(\tau \to K \nu)$ are reasonably consistent with unitarity determined from$^{[3]}$. Both of these measurements are dominated by the $\text{BaBar}$ measurement $^{[21]}$. The value of $|V_{us}|$ extracted using the FESR method deviation from unitarity is $3.4\sigma$. With the recent upper-limits on the unmeasured $\tau$ decay modes, the possibility of this deviation resulting from missing decay modes is becoming smaller. However, measurements of the hadronic $\tau$ decays at BELLE and $\text{BaBar}$ seem to be systematically lower then the previous world averages. This problem could be a result of differences in the definitions of the decay modes between the B-Factories and previous experiments or an artifact from only having updated a subset of all the $\tau$ hadronic branching fractions. Therefore, further results are needed before drawing any significant conclusions. On the theoretical side, the deviation could be related to convergence problems with the weights employed for the FESR which are not taken in to account by the systematic uncertainties $^{[10]}$ $^{30}$ $^{31}$.
Figure 1: An update of $|V_{us}|$ from the HFAG 2012 report [4] for the hadronic $\tau$ 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 [2], $K_{l2}$ decays [2] and the unitarity constraint [3].

References

[1] N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963).
[2] M. Antonelli, V. Cirigliano, G. Isidori, F. Mescia, M. Moulson, H. Neufeld, E. Passemard and M. Palutan et al., Eur. Phys. J. C 69, 399 (2010) [arXiv:1005.2323 [hep-ph]].
[3] J. C. Hardy and I. S. Towner, Phys. Rev. C 79, 055502 (2009) [arXiv:0812.1202 [nucl-ex]].
[4] Y. Amhis et al. [Heavy Flavor Averaging Group Collaboration], arXiv:1207.1158 [hep-ex].
[5] M. Krawczyk and D. Temes, Eur. Phys. J. C 44, 435 (2005) [hep-ph/0410248].
[6] I. Dorsner, S. Fajfer, J. F. Kamenik and N. Kosnik, Phys. Lett. B 682, 67 (2009) [arXiv:0906.5585 [hep-ph]].
[7] W. Loinaz, N. Okamura, T. Takeuchi and L. C. R. Wijewardhana, Phys. Rev. D 67, 073012 (2003) [hep-ph/0210193].
[8] A. Czarnecki, W. J. Marciano and A. Sirlin, Phys. Rev. D 70, 093006 (2004) [hep-ph/0406324].
[9] W. J. Marciano, PoS KAON, 003 (2008).
[10] K. Maltman, C. E. Wolfe, S. Banerjee, J. M. Roney and I. Nugent, Int. J. Mod. Phys. A 23, 3191 (2008) [arXiv:0807.3195 [hep-ph]].
[11] J. Laiho, E. Lunghi and R. S. Van de Water, Phys. Rev. D 81, 034503 (2010) [arXiv:0910.2928 [hep-ph]].
[12] S. Banerjee [BaBar Collaboration], [arXiv:0811.1429 [hep-ex]].
[13] W. J. Marciano and A. Sirlin, Lett. 71, 3629 (1993).
[14] W. J. Marciano, Phys. Rev. Lett. 93, 231803 (2004) [hep-ph/0402299].
[15] J. Erler, Rev. Mex. Fis. 50, 200 (2004) [hep-ph/0211345].
[16] J. P. Lees [BaBar Collaboration], [arXiv:1208.0376 [hep-ex]].
[17] J. P. Lees et al. [BaBar Collaboration], [arXiv:1209.2734 [hep-ex]].
[18] M. J. Lee et al. [Belle Collaboration], Phys. Rev. D 81, 113007 (2010) [arXiv:1001.0083 [hep-ex]].
[19] S. Ryu et al. [Belle collaboration], Presented at the 12th International Workshop on Tau Lepton Physics Nagoya, Japan, 17-21 September, 2012, To be published in Nucl. Phys. B Proceedings Supplement.
[20] I. M. Nugent et al. [BABAR collaboration], Presented at the 12th International Workshop on Tau Lepton Physics Nagoya, Japan, 17-21 September, 2012, To be published in Nucl. Phys. B Proceedings Supplement.
[21] B. Aubert et al. [BABAR Collaboration], Phys. Rev. Lett. 105, 051602 (2010) [arXiv:0912.0242 [hep-ex]].
[22] B. Aubert et al. [BABAR Collaboration], Phys. Rev. D 76, 051104 (2007) [arXiv:0707.2922 [hep-ex]].
[23] D. Epifanov et al. [Belle Collaboration], Phys. Lett. B 654, 65 (2007) [arXiv:0706.2231 [hep-ex]].
[24] B. Aubert et al. [BABAR Collaboration], Nucl. Phys. Proc. Suppl. 189, 193 (2009) [arXiv:0808.1121 [hep-ex]].
[25] S. Ryu et al. [Belle collaboration], Presented at the International Workshop on $e^+e^-$ collisions from phi to psi (PHIPSI11), Novosibirsk, 19-22 Sep, 2011. Nucl. Phys. B Proc. Suppl. 00 (2011) 1-5.
[26] S. Paramesvaran [BaBar Collaboration], [hep-ex].
[27] B. Aubert et al. [BABAR Collaboration], Phys. Rev. Lett. 100, 011801 (2008) [arXiv:0707.2981 [hep-ex]].
[28] K. Inami et al. [Belle Collaboration], Phys. Lett. B 672, 209 (2009) [arXiv:0811.0088 [hep-ex]].
[29] P. del Amo Sanchez et al. [BaBar Collaboration], Phys. Rev. D 83, 032002 (2011) [arXiv:1011.3917 [hep-ex]].

[30] J. Kambor and K. Maltman, Phys. Rev. D 62, 093023 (2000) [hep-ph/0005156].

[31] K. Maltman, Nucl. Phys. Proc. Suppl. 218, 146 (2011) [arXiv:1011.6391 [hep-ph]].