HFLAV τ branching fractions fit and measurements of $|V_{us}|$ with τ lepton data

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Abstract

We report the status of the Heavy Flavour Averaging Group (HFLAV) averages of the τ lepton measurements We then update the latest published HFLAV global fit of the τ lepton branching fractions (Spring 2017) with recent results by BABAR. We use the fit results to update the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{us}|$ measurements with the τ branching fractions. We combine the direct τ branching fraction measurements with indirect predictions using kaon branching fractions measurements to improve the determination of $|V_{us}|$ using τ branching fractions. The $|V_{us}|$ determinations based on the inclusive branching fraction of τ to strange final states are about 3σ lower than the $|V_{us}|$ determination from the CKM matrix unitarity.

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1 Introduction

The τ subgroup of the Heavy Flavour Averaging Group (HFLAV) provides a global fit of the τ branching fractions, the lepton universality tests and the $|V_{us}|$ determination based on τ measurements. The latest published report for the τ lepton is labelled "Spring 2017" [1]. A version of the HFLAV τ branching fractions fit with unitarity constraint is published on the Review of Particle Physics [2] (RPP). There are additional minor differences between the two fits [1,3]. The fit results are used to test lepton universality and to compute $|V_{us}|$ [1].

The HFLAV-Tau group collects and combines also a list of upper limits set by searches of lepton-flavour-violating τ decays [1].

In the following, we update the HFLAV-Tau global fit inputs with two BABAR measurements that became public in 2018 [4,5] and we update the $|V_{us}|$ determinations based on τ data. The new results have a negligible effect on the lepton universality tests.

Finally, we add to the fit input measurements of three τ branching fractions that are indirectly determined using measurements of kaon branching fractions [6], in order to improve the precision on $|V_{us}|$.

2 New τ branching fraction measurements

Since the last HFLAV report, BABAR published [4] a measurement of

$$B(\tau^- \to K^- K^0 \nu_\tau) = (14.78 \pm 0.22 \pm 0.40)10^{-4}$$

and presented [5] preliminary measurements of

$$\begin{aligned}
B(\tau^- \to K^- \nu_\tau) &= (7.174 \pm 0.033 \pm 0.213)10^{-3} \,, \\
B(\tau^- \to K^- \pi^0 \nu_\tau) &= (5.054 \pm 0.021 \pm 0.148)10^{-3} \,, \\
B(\tau^- \to K^- 2\pi^0 \nu_\tau (ex.K^0)) &= (6.151 \pm 0.117 \pm 0.338)10^{-4} \,, \\
B(\tau^- \to K^- 3\pi^0 \nu_\tau (ex.K^0, \eta)) &= (1.246 \pm 0.164 \pm 0.238)10^{-4} \,, \\
B(\tau^- \to K^- 3\pi^0 \nu_\tau (ex.K^0, \eta)) &= (1.168 \pm 0.006 \pm 0.038)10^{-2} \,, \\
B(\tau^- \to K^- 4\pi^0 \nu_\tau (ex.K^0, \eta)) &= (9.020 \pm 0.400 \pm 0.652)10^{-4} \,.
\end{aligned}$$

3 $|V_{us}|$ determination including the 2018 BABAR results

We add the measurements listed in the previous section to the HFLAV-Tau global fit, removing a former BABAR measurement of $B(\tau^- \to K^- \pi^0 \nu_\tau)$ [7] that has been superseded [5]. The new measurements of the branching fractions τ decaying to a kaon and 0, 1, 2, 3 π^0's improve the experimental resolution on several modes that most contribute to the uncertainty on $|V_{us}|$.

We compute $|V_{us}|_{\tau s}$ using the total branching fraction of the τ to strange final states following Ref. [8]:

$$|V_{us}|_{\tau s} = \sqrt{R_s \Big/ \left[\frac{R_{\text{VA}}}{|V_{ud}|^2} - \delta R_{\text{theory}} \right]} = 0.2195 \pm 0.0019 \,,$$

where $|V_{ud}| = 0.97420 \pm 0.00021$ [9], R_s and R_{VA} are the τ hadronic partial widths to strange and to non-strange hadronic final states (Γ_s and Γ_{had}) divided by the universality-improved branching fraction $B(\tau \to e\nu\bar{\nu}) = B_e^{\text{uni}} = (17.814 \pm 0.022)\%$ [1, 3], and the SU(3)-breaking term $\delta R_{\text{theory}} = 0.242 \pm 0.033$ is computed using inputs from Ref. [8] and $m_s = (95.00 \pm 6.70)\,\text{MeV}$ [2] (the uncertainties on m_s have been symmetrized).

We compute also

$$|V_{us}|_{\tau K/\pi} = |V_{ud}| \frac{f_{\pi\pm}}{f_{K\pm}} \frac{m_\tau^2 - m_\pi^2}{m_\tau^2 - m_K^2} \sqrt{\frac{B(\tau^- \to K^- \nu_\tau)}{B(\tau \to \pi^- \nu_\tau)} \frac{R_{\tau/\pi}}{R_{\tau/K}} \frac{1}{R_{\tau K/\tau\pi}}} = 0.2236 \pm 0.0016 \,,$$

where $f_{K\pm}/f_{\pi\pm} = 1.193 \pm 0.003$ from the FLAG 2016 Lattice averages with $N_f = 2+1+1$ [10–13] (the same value persists in the FLAG 2017 web update). The radiative correction terms are $R_{\tau/K} = 1 + (0.90 \pm 0.22)\%$, $R_{\tau/\pi} = 1 + (0.16 \pm 0.14)\%$ [14–17], $R_{\tau K/\tau\pi} = 1 + (-0.69 \pm 0.17)\%$ [18–20]. The third value differs from the one quoted in the Spring 2017 HFLAV-Tau report [1], which incorrectly included a strong isospin-breaking correction that is not needed when using $f_{K\pm}/f_{\pi\pm}$ rather than its isospin-limit variant. The other parameters are taken from the Review of Particle Physics (RPP) 2018 [2].

Averaging the two above $|V_{us}|$ determinations, we obtain $|V_{us}|_\tau = 0.2220 \pm 0.0014$.

Table 1: Deviations of $|V_{us}|$ computed with τ data with respect to $|V_{us}|$ obtained with CKM unitarity. The second and third row use the $|V_{us}|$ determinations performed above.

	$\Delta\,|V_{us}|_{\tau s}$ [σ]	$\Delta\,|V_{us}|_{\tau K/\pi}$ [σ]	$\Delta\,|V_{us}|_{\tau}$ [σ]
HFLAV Spring 2017	-3.0	-1.0	-2.3
HFLAV + BABAR 2018	-2.9	-1.1	-2.3
HFLAV + BABAR + kaon predictions	-2.7	-0.1	-0.9

4 τ branching fraction predictions from kaon measurements

Assuming the validity of the Standard Model (SM), three τ branching fractions have been computed using the precisely measured $K_{\ell 2}$ and $K_{\ell 3}$ branching fractions and the measured $\tau^- \to (K\pi)^- \nu_\tau$ spectra [6]:

$$B(\tau^- \to K^- \nu_\tau) = (0.713 \pm 0.003)\% \,,$$
$$B(\tau^- \to K^- \pi^0 \nu_\tau) = (0.471 \pm 0.018)\% \,,$$
$$B(\tau^- \to K^0 \pi^- \nu_\tau) = (0.857 \pm 0.030)\% \,.$$

The uncertainties on the last two results are fully correlated. It has been observed [6,18] that all the above indirect values are higher than the corresponding directly measured τ branching fractions. If the indirect values replace the direct ones, $|V_{us}| = 0.2207 \pm 0.027$ [6].

We add the kaon-indirect determinations of the three above τ branching fractions to the data set used in the previous section in order to obtain improved calculations of $|V_{us}|_{\tau s} = 0.2202 \pm 0.0018$, $|V_{us}|_{\tau K/\pi} = 0.22546 \pm 0.00097$, $|V_{us}|_{\tau} = 0.22439 \pm 0.00088$.

5 Consistency of $|V_{us}|$ with the CKM matrix unitarity

Assuming the CKM matrix unitarity,

$$|V_{us}|_{uni} = \sqrt{1 - |V_{ud}|^2 - |V_{ub}|^2} = 0.22565 \pm 0.00089 \,,$$

using $|V_{ud}| = 0.97420 \pm 0.00021$ [9] and $|V_{ub}| = (0.3940 \pm 0.0360)10^{-2}$ [2]. Table 1 summarizes the residuals, expressed as numbers of standard deviations, of the above mentioned $|V_{us}|$ determinations with respect to the $|V_{us}|$ computation from the CKM matrix unitarity. $|V_{us}|$ computed with the τ-inclusive method is significantly lower, but the significance of the discrepancy is mildly reduced alongside a mild progress in the experimental resolution.

6 Conclusions

Figure 1 reports the $|V_{us}|_{\tau s}$ determinations described above, a determination of $|V_{us}|_{\tau s}$ obtained replacing some τ branching fractions measurements with the indirect predictions based on kaon branching fractions [6], and other more complex determinations that use the τ spectral functions [21] and Lattice QCD techniques [22]. Updates on the last two determinations have been presented at the Tau 2018 workshop [23]. The last four determinations use an older and in some cases partial set of experimental τ branching fractions measurements.

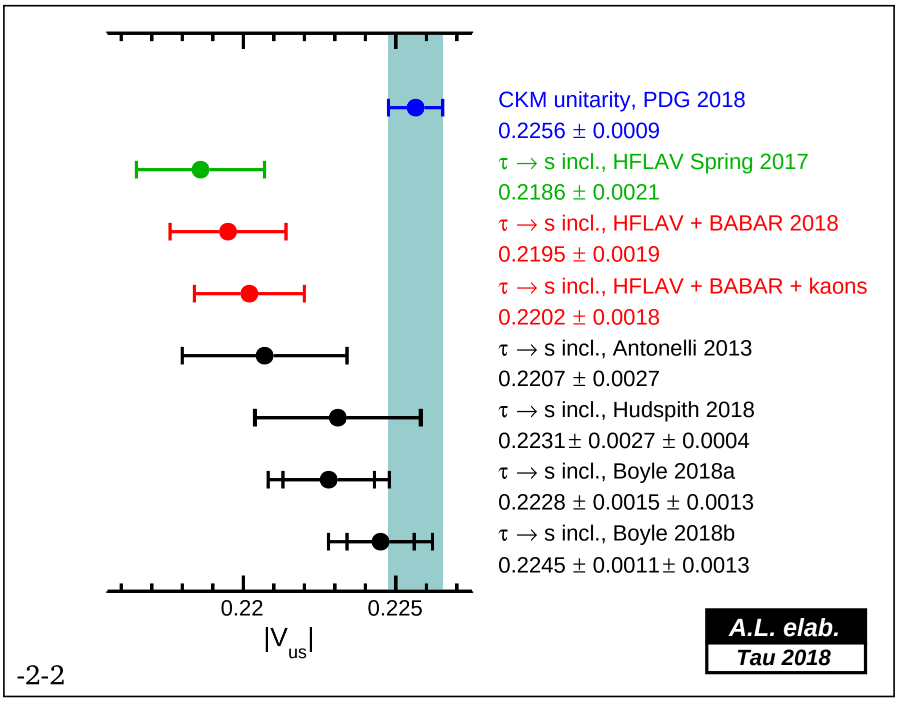

Figure 1: $|V_{us}|_{\tau s}$ determinations obtained in this document, from the top: $|V_{us}|_{uni}$, $|V_{us}|_{\tau s}$ with the HFLAV Spring 2017 fit, after adding the BABAR 2018 data, after adding both the BABAR 2018 and the kaon indirect predictions, from Ref. [6], from Ref. [21], and two determinations from Ref. [22].

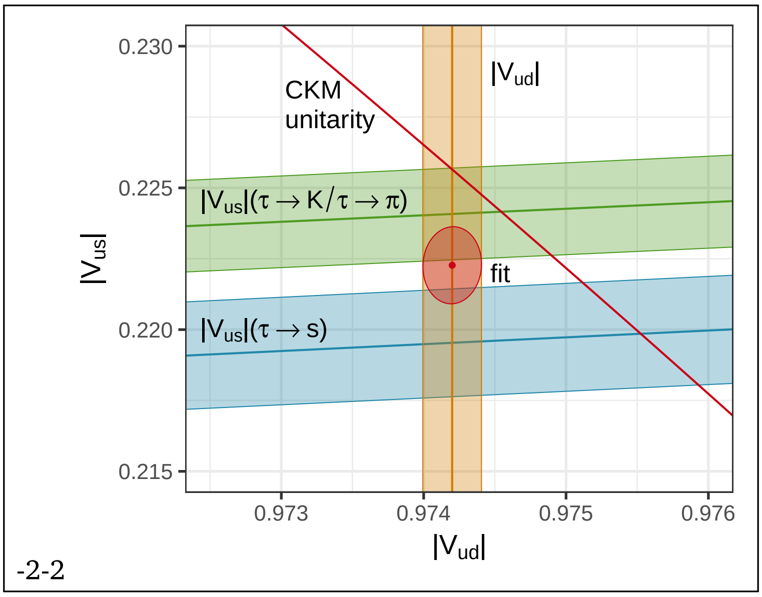

Figure 2: Results of a $|V_{ud}|$-$|V_{us}|$ simultaneous fit. The bands describe the constraints corresponding to the $|V_{ud}|$ measurement, the $|V_{us}|_{\tau s}$ and the $|V_{us}|_{\tau K/\pi}$ determinations that use the τ measurements. The oblique line corresponds to the CKM matrix unitarity constraint. The ellipse corresponds to 1σ uncertainty on the $|V_{ud}|$ and $|V_{us}|$ fit results.

The τ based $|V_{us}|$ determinations use the $|V_{ud}|$ measurements as input. The dependence on $|V_{ud}|$ is however very small, and there is in first approximation negligible correlation between $|V_{us}|$ and $|V_{ud}|$ when doing a simultaneous fit. Figure 2 shows the results of a $|V_{ud}|$-$|V_{us}|$ simultaneous fit on the τ measurements corresponding to the HFLAV Spring 2017 fit and the BABAR 2018 results. The fit results are:

$$\begin{aligned} |V_{ud}| &= 0.97420 \pm 0.00021, \\ |V_{us}| &= 0.2223 \quad \pm 0.0014, \\ |V_{ud}|\text{-}|V_{us}| &\text{ correlation} = 0.035. \end{aligned}$$

Tables 2 and 3 report the contributions to the $|V_{us}|_{\tau s}$ uncertainty before and after the BABAR 2018 results. The largest contributions come from the τ branching fractions to strange final states and from the theory. The BABAR 2018 measurements reduced significantly several large contributions. High multiplicity τ decays to strange final states dominate the $|V_{us}|_{\tau s}$ uncertainty. The Belle II super flavour factory will offer the opportunity to improve the experimental precision on the τ strange branching fractions. More precise τ branching fractions and spectral function measurements will help improving also the theory uncertainty.

Table 2: Contributions to the $|V_{us}|_{\tau s}$ uncertainty in percent before the BABAR 2018 results.

$\pi^-\bar{K}^0\pi^0\pi^0\nu_\tau$ (ex. K^0)	0.3963
$K^-2\pi^0\nu_\tau$ (ex. K^0)	0.3789
$K^-3\pi^0\nu_\tau$ (ex. K^0,η)	0.3714
$\bar{K}^0h^-h^-h^+\nu_\tau$	0.3478
$K^-\pi^0\nu_\tau$	0.2561
$K^-\pi^-\pi^+\pi^0\nu_\tau$ (ex. K^0,ω,η)	0.2456
$\pi^-\bar{K}^0\nu_\tau$	0.2424
$\pi^-\bar{K}^0\pi^0\nu_\tau$	0.2219
$K^-\nu_\tau$	0.1646
$K^-\omega\nu_\tau$	0.1585
$K^-\pi^-\pi^+\nu_\tau$ (ex. K^0,ω)	0.1157
$\pi^-\bar{K}^0\eta\nu_\tau$	0.0256
$K^-\pi^0\eta\nu_\tau$	0.0200
$K^-\eta\nu_\tau$	0.0138
$K^-\phi\nu_\tau$ ($\phi\to K^+K^-$)	0.0138
$K^-\phi\nu_\tau$ ($\phi\to K^0_SK^0_L$)	0.0096
$K^-2\pi^-2\pi^+\nu_\tau$ (ex. K^0)	0.0021
$K^-2\pi^-2\pi^+\pi^0\nu_\tau$ (ex. K^0)	0.0010
$\tau\to$ non-strange	0.0896
B_e^{univ}	0.0045
theory	0.4861

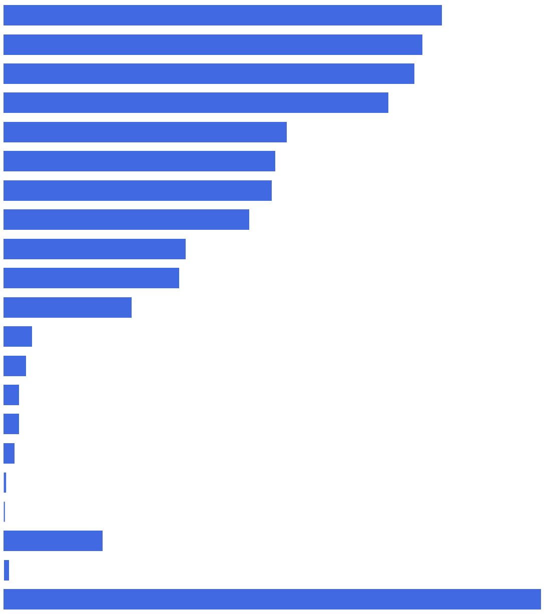

Table 3: Contributions to the $|V_{us}|_{\tau s}$ uncertainty in percent after the BABAR 2018 results.

$\pi^- \bar{K}^0 \pi^0 \pi^0 \nu_\tau$ (ex. K^0)	0.3931
$\bar{K}^0 h^- h^- h^+ \nu_\tau$	0.3450
$K^- \pi^- \pi^+ \pi^0 \nu_\tau$ (ex. K^0, ω, η)	0.2436
$\pi^- \bar{K}^0 \nu_\tau$	0.2372
$\pi^- \bar{K}^0 \pi^0 \nu_\tau$	0.2200
$K^- \omega \nu_\tau$	0.1572
$K^- \pi^0 \nu_\tau$	0.1554
$K^- \nu_\tau$	0.1459
$K^- \pi^- \pi^+ \nu_\tau$ (ex. K^0, ω)	0.1147
$K^- 2\pi^0 \nu_\tau$ (ex. K^0)	0.0460
$K^- 3\pi^0 \nu_\tau$ (ex. K^0, η)	0.0449
$\pi^- \bar{K}^0 \eta \nu_\tau$	0.0254
$K^- \pi^0 \eta \nu_\tau$	0.0198
$K^- \eta \nu_\tau$	0.0137
$K^- \phi \nu_\tau$ ($\phi \to K^+ K^-$)	0.0136
$K^- \phi \nu_\tau$ ($\phi \to K^0_S K^0_L$)	0.0095
$K^- 2\pi^- 2\pi^+ \nu_\tau$ (ex. K^0)	0.0021
$K^- 2\pi^- 2\pi^+ \pi^0 \nu_\tau$ (ex. K^0)	0.0010
$\tau \to$ non-strange	0.0855
B_e^{univ}	0.0045
theory	0.4863

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