Lepton Flavour Universality tests and determination of Vus using the tau branching fractions fit

HFLAV Tau

Alberto Lusiani
on behalf of the HFLAV group

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Abstract

We describe the updated tau lepton averages performed by the Heavy Flavour Averaging Group (HFLAV) for the incoming edition of the Heavy Flavour measurements averages, and we use the results to update several Lepton Flavour Universality tests and the computation of $|V_{us}|$ with tau measurements.

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Tau branching fraction fit inputs

	inputs	examples
171	measurements of τ branching fractions & branching ratios	$\mathcal{B}(\tau^- \to \pi^-\nu_\tau)$, $\dfrac{\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)}{\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)}$
1	nuisance fit parameter measurement (new feature)	$\mathcal{B}(a_1^- \to \pi^-\gamma) = 0.0021 \pm 0.0008$ [Schael et al., 2005]
91	constraints	$\mathcal{B}_{3/5} = \dfrac{\mathcal{B}_3}{\mathcal{B}_5}$ with • $\mathcal{B}_{3/5} = \dfrac{\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)}{\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)}$, • $\mathcal{B}_3 = \mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$, $\mathcal{B}_5 = \mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)$
1	uncertainty scale factor	5.44 scale factor applied to inconsistent BaBar and Belle $\mathcal{B}(\tau^- \to K^-K^-K^+\nu_\tau)$

χ^2 minimization

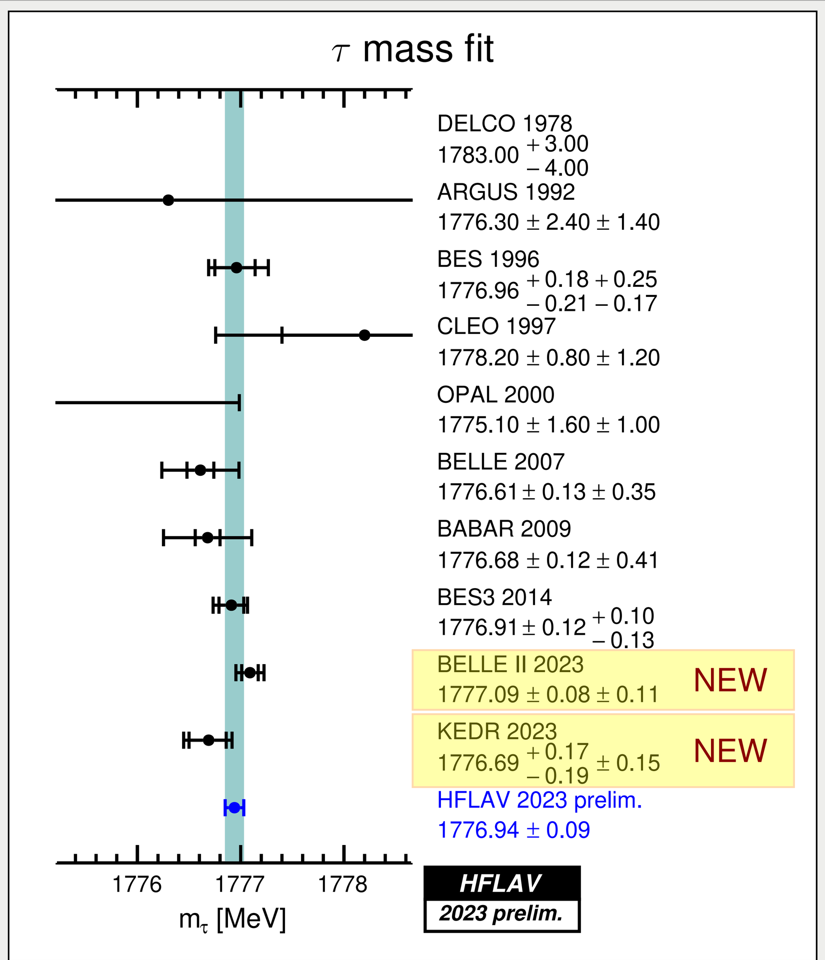
$$\chi^2 = \sum_{ijkl} (m_i - M_{ik}q_k) \left(V^{-1}\right)_{ij} \left(m_j - M_{jl}q_l\right) + \sum_r \frac{(n_r - p_r)^2}{\sigma^2_{n_r}},$$

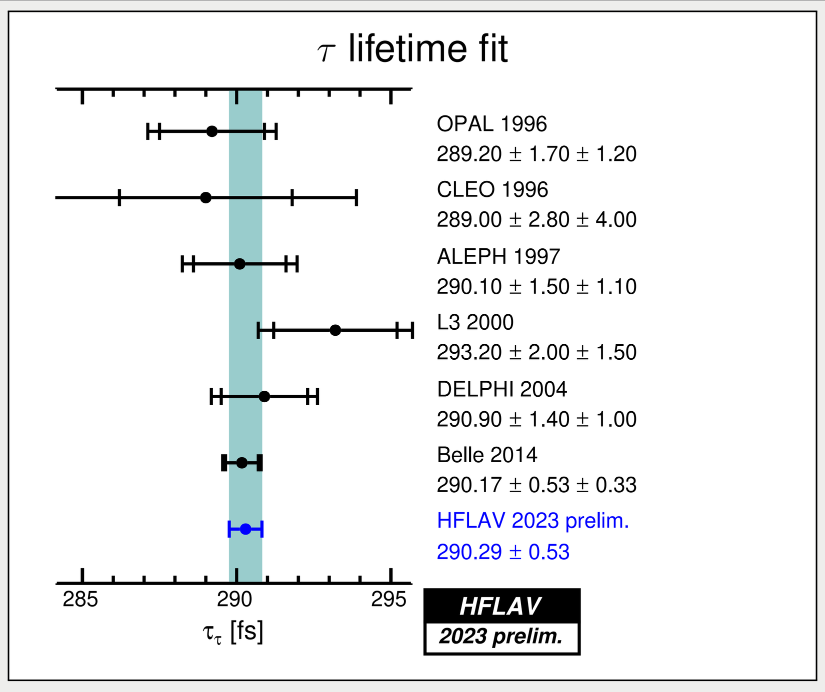
m_i	measurement result
q_k	fit parameter
M_{ik}	model matrix applied to fit parameters to predict measurements
V_{ij}	measurements covariance matrix
p_r	nuisance fit parameter
$n_r \pm \sigma_{n_r}$	measurement of nuisance fit parameter

Tau branching fractions fit results

137 fit parameters 1 nuisance fit parameter (new feature)
covariance matrix of fit parameters and nuisance fit parameters
$\chi^2/\text{d.o.f.} = 138/125$ $P(\chi^2) = 20.2\%$
unitarity residual $\mathcal{B}_{ur} = 1 - \mathcal{B}_{all} = 0.0007 \pm 0.0011$

Tau mass and lifetime fits





	τ mass [MeV]
PDG 2023	1776.86 ± 0.12
PDG 2024	1776.93 ± 0.09
HFLAV 2023 prelim.	1776.94 ± 0.09

(slightly different treatment of asymmetric uncertainties)

Ratio of tau hadronic to leptonic branching fractions

$\mathcal{B}_e^{\text{uni}} = (17.815 \pm 0.023)\%$, average of (see [Davier, Hocker, and Zhang, 2006])

- $\mathcal{B}_e = \mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)$
- $\mathcal{B}_e$ from $\mathcal{B}_\mu = \mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$ assuming Lepton Flavour Universality
- $\mathcal{B}_e$ from τ lifetime assuming Lepton Flavour Universality

$$R_{\text{had}} = \frac{\Gamma(\tau \to \text{hadrons})}{\Gamma(\tau \to e\bar{\nu}_e\nu_\tau)} = \frac{\mathcal{B}_{\text{had}}}{\mathcal{B}_e^{\text{uni}}} = 3.634 \pm 0.008$$

Lepton Flavour Universality: coupling ratios

$$\left(\frac{g_\tau}{g_\mu}\right) = \sqrt{\frac{\mathcal{B}_{\tau e}\,\tau_\mu m_\mu^5 f_{\mu e} R_\gamma^\mu R_W^{\mu e}}{\mathcal{B}_{\mu e}\,\tau_\tau m_\tau^5 f_{\tau e} R_\gamma^\tau R_W^{\tau e}}} = 1.0016 \pm 0.0014 \qquad \left(\frac{g_\tau}{g_e}\right) = \sqrt{\frac{\mathcal{B}_{\tau\mu}\,\tau_\mu m_\mu^5 f_{\mu e} R_\gamma^\mu R_W^{\mu e}}{\mathcal{B}_{\mu e}\,\tau_\tau m_\tau^5 f_{\tau\mu} R_\gamma^\tau R_W^{\tau\mu}}} = 1.0018 \pm 0.0014$$

$$\left(\frac{g_\mu}{g_e}\right) = \sqrt{\frac{\mathcal{B}_{\tau\mu}\, f_{\tau e} R^{\tau e}}{\mathcal{B}_{\tau e}\, f_{\tau\mu} R^{\tau\mu}}} = 1.0002 \pm 0.0011$$

improved by Belle II recent prelim. measurement of $\mathcal{B}_{\tau\mu}/\mathcal{B}_{\tau e}$ [Adachi et al., 2024], was 1.0019 ± 0.0014

$$f\left(\frac{m_\rho^2}{m_\lambda^2}\right) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x \quad \text{with} \quad x = \frac{m_\rho^2}{m_\lambda^2}, \quad \lambda, \rho = \text{lepton flavours}$$

R_γ^λ, $R_W^{\lambda\rho}$ radiative corrections [Pich, 2014]

Lepton Flavour Universality, g_τ/g_μ coupling ratio

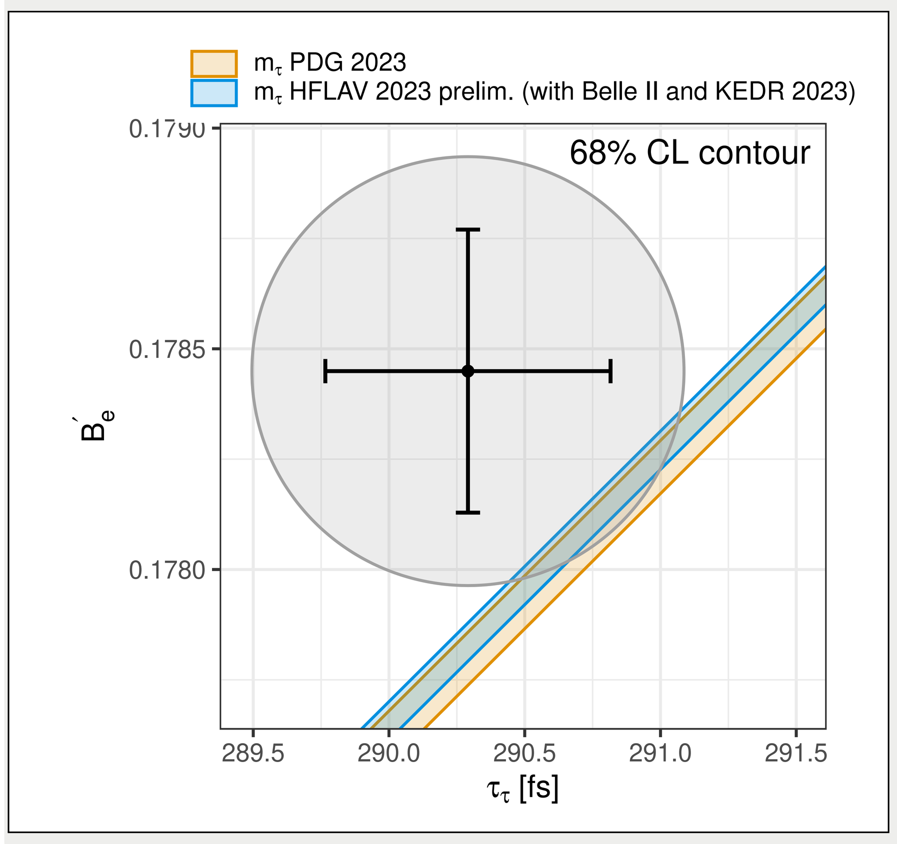
$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = \sqrt{\frac{\mathcal{B}(\tau \to \pi\nu_\tau)}{\mathcal{B}(\pi \to \mu\bar{\nu}_\mu)} \frac{2m_\pi m_\mu^2 \tau_\pi}{(1 + \delta R_{\tau/\pi}) m_\tau^3 \tau_\tau} \frac{1 - m_\mu^2/m_\pi^2}{1 - m_\pi^2/m_\tau^2}} = 0.996 \pm 0.004$$

$$\left(\frac{g_\tau}{g_\mu}\right)_K = \sqrt{\frac{\mathcal{B}(\tau \to K\nu_\tau)}{\mathcal{B}(K \to \mu\bar{\nu}_\mu)} \frac{2m_K m_\mu^2 \tau_K}{(1 + \delta R_{\tau/K}) m_\tau^3 \tau_\tau} \frac{1 - m_\mu^2/m_K^2}{1 - m_K^2/m_\tau^2}} = 0.986 \pm 0.008$$

$\delta R_{\tau/\pi}$, $\delta R_{\tau/K}$ radiative corrections [Arroyo-Ureña et al., 2021; Amhis et al., 2023]

$$\left(\frac{g_\tau}{g_\mu}\right)_{\tau+\pi+K} = 1.0011 \pm 0.0014$$

“Canonical” tau Lepton Flavour Universality plot



$\mathcal{B}'_e$ = average of $\mathcal{B}_e = \mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)$ and

$\mathcal{B}_e$ prediction from $\mathcal{B}_\mu$, $\mathcal{B}_\mu \dfrac{f(m_e^2/m_\tau^2)\, R_W^{\tau e}}{f(m_\mu^2/m_\tau^2)\, R_W^{\tau\mu}}$

proportional to g_e, g_μ

$\mathcal{B}'_e$ Standard Model prediction from tau lifetime

$$\mathcal{B}(\mu \to e\bar{\nu}_e\nu_\mu) \frac{\tau_\tau m_\tau^5 f(m_e^2/m_\tau^2)\, R_W^{\tau e} R_\gamma^\tau}{\tau_\mu m_\mu^5 f(m_e^2/m_\mu^2)\, R_W^{\mu e} R_\gamma^\mu}$$

represented by oblique bands, whose widths are determined primarly by the tau mass precision (improved by recent Belle II [Adachi et al., 2023] & KEDR [Anashin et al., 2023] results)

$|V_{us}|$ from $\mathcal{B}(\tau \to$ “strange hadronic system” $+ \nu)$, – “inclusive”

$$|V_{us}|_{\tau s} = \sqrt{R_s \Big/ \left[\frac{R_{VA}}{|V_{ud}|^2} - \delta R_{\tau\text{-}SU(3)\text{-break}}\right]} \quad \text{[Gámiz et al., 2003]}$$

- $\delta R_{\tau\text{-}SU(3)\text{-break}}$ accounts for $SU(3)$-breaking effects
- $R_s = \mathcal{B}(\tau \to \text{strange hadronic})/\mathcal{B}_e^{\text{uni}}$, $R_{VA} = \mathcal{B}(\tau \to \text{non-strange hadronic})/\mathcal{B}_e^{\text{uni}}$

$|V_{us}|$ from $\mathcal{B}(\tau \to \pi\nu)/\mathcal{B}(\tau \to K\nu)$ and $\mathcal{B}(\tau \to \pi\nu)$ – “exclusive”

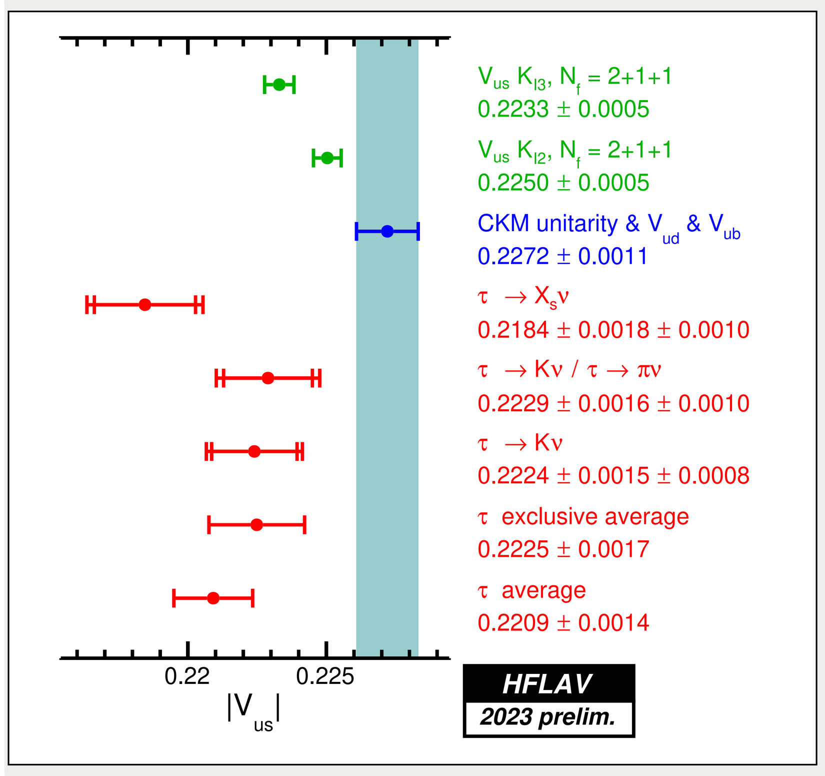
$$|V_{us}| = |V_{ud}| \sqrt{\frac{\mathcal{B}(\tau^- \to K^-\nu_\tau)}{\mathcal{B}(\tau^- \to \pi^-\nu_\tau)} \frac{f_{\pi\pm}^2}{f_{K\pm}^2} \left(\frac{m_\tau^2 - m_\pi^2}{m_\tau^2 - m_K^2}\right)^2 \frac{1}{1 + \delta_{\tau K/\tau\pi}}}$$

$$|V_{us}| = \frac{1}{G_F f_{K\pm}\left(1 - m_K^2/m_\tau^2\right)} \sqrt{\frac{16\pi\hbar\mathcal{B}(\tau^- \to K^-\nu_\tau)}{\tau_\tau m_\tau^3 S_{\text{EW}}^{\tau h}(1 + \delta_{\tau K})}}$$

calculations require decay constants (obtained from lattice QCD averages) and radiative corrections

details in incoming HFLAV report (updated from previous HFLAV report)

$|V_{us}|$ from tau measurements



$|V_{us}|$ computed using tau measurements (red) compared with the determinations based on kaon measurements (green) [Cirigliano et al., 2023] and $|V_{us}|$ prediction assuming unitarity of first row of CKM matrix and the measured value of $|V_{ud}|$ [Cirigliano et al., 2023]

details in incoming HFLAV report

References

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