Lepton Flavour Universality tests and determination of $|V_{us}|$ using the HFLAV tau branching fractions fit

for the HFLAV Tau group,

Alberto Lusiani

https://orcid.org/0000-0002-6876-3288

2025 European Physical Society Conference on High Energy Physics (EPS-HEP 2025), Marseille, 7-11 July 2025

HFLAV Tau branching fraction fit

	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)	$\mathcal{B}(a_1^- \to \pi^- \gamma) = 0.0021 \pm 0.0008$ [Phys.Rept. 421 (2005) 191]
91	constraints	$\mathcal{B}_{\tau\to\mu\nu\bar{\nu}/\tau\to e\nu\bar{\nu}} = \mathcal{B}_{\tau\to\mu\nu\bar{\nu}}/\mathcal{B}_{\tau\to e\nu\bar{\nu}}$ tau-decay final states related through different η, ω decay modes
1	uncertainty scale factor	5.44 scale factor for inconsistent BABAR/ Belle $\mathcal{B}(\tau^- \to K^- K^- K^+ \nu_\tau)$

external uncertain parameters: correct for updated values, account from induced uncertainties' correlations

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

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

- HFLAV unitarity-constrained tau BR fit used for PDG tau BR "fit"averages
  - use of nuisance fit parameter removes some modifications of HFLAV tau BR fit for PDG "fit" averages

Lepton universality tests with tau compared with other measurements

2013 [A.Pich, Precision Tau Physics (2014)]

$|g_\mu/g_e|$	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$ 1.0018(14)	$\Gamma_{\pi\to\mu}/\Gamma_{\pi\to e}$ 1.0021(16)	$\Gamma_{K\to\mu}/\Gamma_{K\to e}$ 0.9978(20)	$\Gamma_{K\to\pi\mu}/\Gamma_{K\to\pi e}$ 1.0010(25)	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$ 0.996(10)
$|g_\tau/g_\mu|$	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$ 1.0011(15)	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$ 0.9962(27)	$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$ 0.9858(70)		$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$ 1.034(13)
$|g_\tau/g_e|$	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$ 1.0030(15)				$\Gamma_{W\to\tau}/\Gamma_{W\to e}$ 1.031(13)

2024 [V.Cirigliano *et al.*, 2022] [HFLAV 2023 report] [PDG 2024]

$|g_\mu/g_e|$	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$ 1.002(11)	$\Gamma_{\pi\to\mu}/\Gamma_{\pi\to e}$ 1.0010(9)	$\Gamma_{K\to\mu}/\Gamma_{K\to e}$ 0.9978(18)	$\Gamma_{K\to\pi\mu}/\Gamma_{K\to\pi e}$ 1.0009(18)	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$ 1.001(3)
$|g_\tau/g_\mu|$	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$ 1.0016(14)	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$ 0.9958(38)	$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$ 0.9856(75)		$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$ 1.007(10)
$|g_\tau/g_e|$	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$ 1.0018(14)				$\Gamma_{W\to\tau}/\Gamma_{W\to e}$ 1.008(10)

Lepton universality tests with tau leptonic branching fractions

$$\Gamma[\mathcal{L} \to \nu_\mathcal{L} \ell \bar{\nu}_\ell(\gamma)] = \Gamma_{\mathcal{L}\ell} = \Gamma_\mathcal{L} \mathcal{B}_{\mathcal{L}\ell} = \frac{\mathcal{B}_{\mathcal{L}\ell}}{\tau_\mathcal{L}} = \frac{G_\mathcal{L} G_\ell m_\mathcal{L}^5}{192\pi^3} f^{\mathcal{L}\ell} \left(1 + \delta R_\gamma^{\mathcal{L}\ell}\right) \left(1 + \delta R_W^{\mathcal{L}\ell}\right)$$

$$G_\mathcal{L} = \frac{g_\mathcal{L}^2}{4\sqrt{2} M_W^2} ; \qquad f^{\mathcal{L}\ell} = 1 - 8\rho + 8\rho^3 - \rho^4 - 12\rho^2 \ln\rho \quad \text{with} \quad \rho = \rho^{\mathcal{L}\ell} = m_\ell^2 / m_\mathcal{L}^2$$

$$\delta R_\gamma^{\mathcal{L}\ell} = \frac{\alpha(m_\mathcal{L})}{2\pi} \left(\frac{25}{4} - \pi^2\right)$$ QED radiative correction, 1st order

$$\delta R_W^{\mathcal{L}\ell} = \frac{3}{5} \frac{m_\mathcal{L}^2}{M_W^2} + \frac{9}{5} \frac{m_\ell^2}{M_W^2}$$ EW radiative correction

[Marciano, 1988], [Pich, Precision Tau Physics, 2014]

$$\delta R_\gamma^{\mathcal{L}\ell} = H_1^{\mathcal{L}\ell} \frac{\alpha(m_\mathcal{L})}{\pi} + H_2^{\mathcal{L}\ell} \frac{\alpha^2(m_\mathcal{L})}{\pi^3} + H_3^{\mathcal{L}\ell} \frac{\alpha^3(m_\mathcal{L})}{\pi^3}$$ QED radiative correction, 3rd order

$$H_1^{\mathcal{L}\ell} = \frac{25}{8} - \frac{\pi^2}{2} - \left(9 + 4\pi^2 + 12 \ln\rho\right)\rho + 16\pi^2 \rho^{\frac{3}{2}} \quad \text{with} \quad \rho = \rho^{\mathcal{L}\ell}$$

$$H_2^{\mathcal{L}\ell} = \frac{156815}{5184} - \frac{518}{81}\pi^2 - \frac{895}{36}\zeta(3) + \frac{67}{720}\pi^4 + \frac{53}{6}\pi^2 \ln 2 + H_{2,\text{had}}^{\mathcal{L}\ell} - \frac{5}{4}\pi^2\sqrt{\rho} \quad \text{with} \quad \rho = \rho^{\mathcal{L}\ell}$$

$H_{2,\text{had}}^{\mu e} = -0.042 \pm 0.002$ $\quad H_{2,\text{had}}^{\tau\mu} = ?$ $\quad H_{2,\text{had}}^{\tau e} = ?$ $\quad$ missing values set to zero in the following

$H_3^{\mu e} = -15.3 \pm 2.3$ $\quad H_3^{\tau\mu} = ?$ $\quad H_3^{\tau e} = ?$ $\quad$ missing values set to zero in the following

[J.Erler & A.Freitas, PDG EW review, 2022] [using modified minimal subtraction scheme ($\overline{\text{MS}}$)]

2nd order QED radiative corrections for leptonic-tau-decays LFU tests

motivation

- estimate uncertainty on QED radiative corrections, usually neglected
- check whether present uncertainties are fine for future prospects at Belle II and FCC-ee

$$\delta R_\gamma^{\mathcal{L}\ell} = H_1^{\mathcal{L}\ell}\frac{\alpha(m_\mathcal{L})}{\pi} + H_2^{\mathcal{L}\ell}\frac{\alpha^2(m_\mathcal{L})}{\pi^3} + H_3^{\mathcal{L}\ell}\frac{\alpha^3(m_\mathcal{L})}{\pi^3}$$ QED radiative correction, 3rd order

$$H_1^{\mathcal{L}\ell} = \frac{25}{8} - \frac{\pi^2}{2} - \left(9 + 4\pi^2 + 12\ln\rho\right)\rho + 16\pi^2\rho^{\frac{3}{2}} \quad \text{with} \quad \rho = \rho^{\mathcal{L}\ell}$$

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[J.Erler & A.Freitas, PDG EW review, 2022] [using modified minimal subtraction scheme ($\overline{\text{MS}}$)]

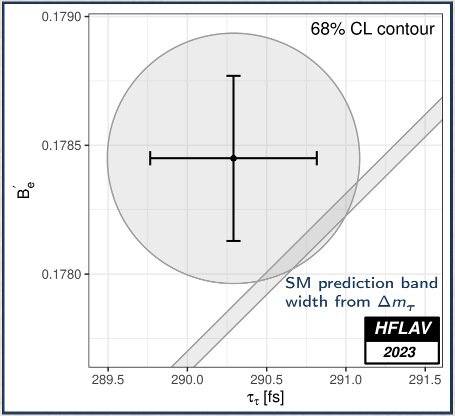
- for tau leptonic partial widths use up to 2nd order QED radiative correction formula without $H_{2,\text{had}}^{\tau(\mu,e)}$, $H_3^{\tau(\mu,e)}$
- tau LFU tests uncertainties up to 2.4 ppm if missing terms $H_{2,\text{had}}^{\tau(\mu,e)} \sim 20 \times H_{2,\text{had}}^{\mu e}$, $H_3^{\tau(\mu,e)} \sim 20 \times H_3^{\mu e}$
- tau mass uncertainty on phase space factors contributes uncertainty up to 1.3 ppm
- $\alpha(m_\tau)$ computed using [F.Jegerlehner 2023 code alphaQEDr23.f], uncertainty up to 0.3 ppm on tau LFU tests

Lepton universality tests with tau leptonic branching fractions

	QED rad. corr. 1st order	QED rad. corr. 2nd order
$\left(\frac{g_\tau}{g_\mu}\right) = \sqrt{\frac{\mathcal{B}_{\tau e}}{\mathcal{B}_{\mu e}} \frac{\tau_\mu m_\mu^5 f^{\mu e}(1+\delta R_\gamma^{\mu e})(1+\delta R_W^{\mu e})}{\tau_\tau m_\tau^5 f^{\tau e}(1+\delta R_\gamma^{\tau e})(1+\delta R_W^{\tau e})}}$	1.0016 ± 0.0014	1.0016 ± 0.0014
$\left(\frac{g_\tau}{g_e}\right) = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\mu e}} \frac{\tau_\mu m_\mu^5 f^{\mu e}(1+\delta R_\gamma^{\mu e})(1+\delta R_W^{\mu e})}{\tau_\tau m_\tau^5 f^{\tau \mu}(1+\delta R_\gamma^{\tau \mu})(1+\delta R_W^{\tau \mu})}}$	1.0018 ± 0.0014	1.0017 ± 0.0014
$\left(\frac{g_\mu}{g_e}\right) = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\tau e}} \frac{f^{\tau e}(1+\delta R_\gamma^{\tau e})(1+\delta R_W^{\tau e})}{f^{\tau \mu}(1+\delta R_\gamma^{\tau \mu})(1+\delta R_W^{\tau \mu})}}$	1.0002 ± 0.0011	1.0001 ± 0.0011

- tau LFU tests limited to 1100–1400 ppm from branching fractions and tau lifetime measurements
- FCC-ee can improve by a factor of 10 (statistically 1000)
- expect sub-ppm uncertainty from further terms of EW radiative corrections
- desirable order-of-magnitude estimate of QED rad. corr. missing terms for tau LFU tests

Canonical tau lepton universality test plot



[HFLAV 2023 report]

$(g_\tau/g_{e\mu}) = 1.0017 \pm 0.0013$

$[g_{e\mu} = g_e = g_\mu$ assuming $g_e = g_\mu]$

$\Delta(g_\tau/g_{e\mu})$ contributions

input	Δinput	$\Delta(g_\tau/g_{e\mu})$
$\mathcal{B}'_{\tau\to e}$	0.180%	0.090%
τ_τ	0.181%	0.090%
m_τ	0.005%	0.012%
total		0.128%

best measurements

$\mathcal{B}'_{\tau\to e}$	ALEPH
τ_τ	Belle
m_τ	Belle II

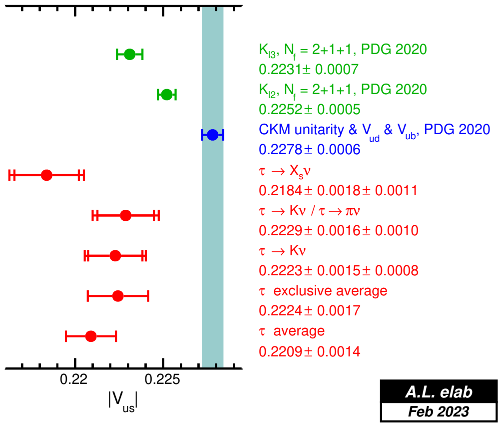
- $\mathcal{B}'(\tau \to e\bar{\nu}\nu) =$ average of $\begin{cases} \mathcal{B}(\tau \to e\bar{\nu}\nu) \\ \mathcal{B}(\tau \to \mu\bar{\nu}\nu) \cdot \dfrac{f^{\tau e} R_\gamma^{\tau e} R_W^{\tau e}}{f^{\tau\mu} R_\gamma^{\tau\mu} R_W^{\tau\mu}} \end{cases}$
- $\dfrac{\mathcal{B}'(\tau \to e\bar{\nu}\nu)\tau_\mu}{\mathcal{B}(\mu \to e\bar{\nu}\nu)\tau_\tau} = \dfrac{g_\tau^2}{g_{e\mu}^2} \dfrac{m_\tau^5 f^{\tau e} R_\gamma^{\tau e} R_W^{\tau e}}{m_\mu^5 f^{\mu e} R_\gamma^{\mu e} R_W^{\mu e}}$
- $\left(\dfrac{g_\tau}{g_{e\mu}}\right)^2 = \dfrac{\mathcal{B}'(\tau \to e\bar{\nu}\nu)}{\mathcal{B}(\mu \to e\bar{\nu}\nu)} \dfrac{\tau_\mu}{\tau_\tau} \dfrac{m_\mu^5}{m_\tau^5} \dfrac{f^{\mu e} R_\gamma^{\mu e} R_W^{\mu e}}{f^{\tau e} R_\gamma^{\tau e} R_W^{\tau e}}$

$|V_{us}|$ from tau measurements

Cabibbo angle anomaly

- 2018: CMK 1st row unitarity OK
- 2019: $\Delta_{\rm CKM} > 3\sigma$ unitarity violation
  - dispersive calculation of Δ_R^V inner or universal electroweak radiative corrections (RC) to super-allowed nuclear beta decays
    Seng, Gorchtein & Ramsey-Musolf, Phys. Rev. D 100, 013001 (2019)
    - $\sim 2\times$ more precise
    - significant shift
- 2020: revision & inflation of $|V_{ud}|$ th. syst. unc.
- 2020-2023: PDG reviews quote $\Delta_{\rm CKM} \sim 3\sigma$
- 2023: short review [Cirigliano *et al.*, 2023]
- 2024: PDG review quotes $\Delta_{\rm CKM} \sim 2\sigma$

$|V_{us}|$ after [Seng *et al.* 2019]



$|V_{us}|$ calculation with "inclusive" tau branching fractions

$|V_{us}|_{\tau\text{-OPE}}$ from $\mathcal{B}(\tau \to X_s \nu)$ and OPE

- $|V_{us}|_{\tau\text{-OPE}} = \sqrt{R_s / \left[\frac{R_{ud}}{|V_{ud}|^2} - \delta R_{\tau,\text{SU3 breaking}} \right]}$ **τ-OPE**
  - $\delta R_{\tau,\text{SU3 breaking}}$ computed with Operator Product Expansion (OPE) perturbative QCD, + m_s W.A.
  - E. Gamiz *et al.*, JHEP 01 (2003) 060, PRL 94 (2005) 011803, Nucl. Phys .Proc. Suppl. 169 (2007) 85, PoS KAON (2008) 008
  - no strong isospin breaking correction

$|V_{us}|_{\tau\text{-latt}}$ from $\mathcal{B}(\tau \to X_s \nu)$ and lattice QCD

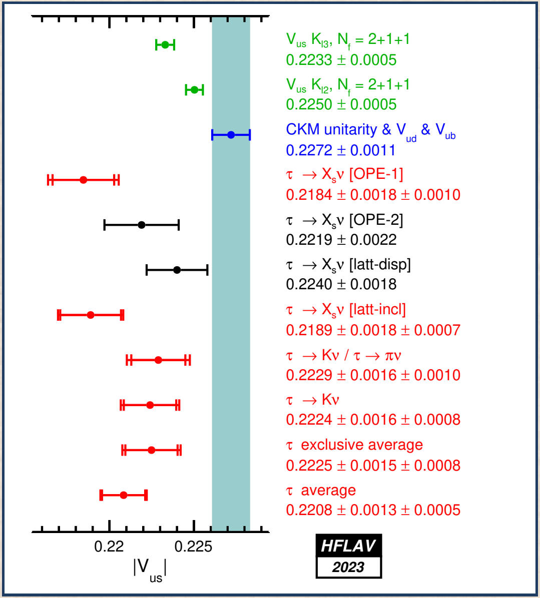
- $|V_{us}|_{\tau\text{-latt}} = \sqrt{\left(\frac{|V_{us}|^2}{R_s} \right)_{\text{latt-incl}} \cdot R_s}$ **τ-latt**
  - $(|V_{us}|^2 / R_s)$ computed with lattice QCD PRL 132 (2024) 26, 261901
  - no strong isospin breaking correction

- $R_s = \mathcal{B}(\tau \to X_s \nu)/\mathcal{B}(\tau \to e\bar{\nu}\nu)$, $R_{ud} = \mathcal{B}(\tau \to X_{ud} \nu)/\mathcal{B}(\tau \to e\bar{\nu}\nu)$

$|V_{us}|$ calculation with "exclusive" tau branching fractions

- $\Gamma(\tau \to \pi \bar{K} \nu_\tau[\gamma]) = \frac{G_F^2 m_\tau^5}{96\pi^3} C_K^2 S_{\text{EW}}^\tau \left(|V_{us}| f^{K\pi}\right)^2 I_K^\tau \left(1 + \delta_{\text{EM}}^{K\tau} + \delta_{\text{SU(2)}}^{K\pi}\right)^2$ $\boxed{\tau \to K\pi}$
  - C_K Clebsch-Gordan coefficients, $= 1$ for K^0, $= 1/2$ for K^-
  - $I_K^\ell =$ phase-space form factor integral
  - Antonelli *et al.*, JHEP 1310 (2013) 070 (2013)
  - (not updated for HFLAV 2023 report)
- $\frac{\mathcal{B}(\tau^- \to \mathcal{B}(\tau^- \to K^- \nu_\tau))}{\mathcal{B}(\tau^- \to \mathcal{B}(\tau^- \to \pi^- \nu_\tau))} = \left(\frac{f^{K\pm}}{f^{\pi\pm}}\right)^2 \frac{|V_{us}|^2_{\tau K/\pi}}{|V_{ud}|^2} \frac{\left(m_\tau^2 - m_K^2\right)^2}{\left(m_\tau^2 - m_\pi^2\right)^2} (1 + \delta R_{\tau K/\tau\pi})$ $\boxed{\tau \to K / \tau \to \pi}$
  - note that $\Delta\delta R_{\tau K/\tau\pi} = \Delta\delta R_{\tau\pi} \oplus \Delta\delta R_{\tau K}$ [PRD 104 9 (2021) L091502]
- $\mathcal{B}(\tau^- \to K^- \nu_\tau) = \frac{1}{16\pi} \left(\frac{G_F}{\hbar^3 c^3}\right)^2 |V_{us}|^2_{\tau K} f_{K\pm}^2 \frac{\tau_\tau}{\hbar} m_\tau^3 c^3 \left(1 - \frac{m_K^2}{m_\tau^2}\right)^2 S_{EW}^\tau (1 + \delta R_{\tau K})$ $\boxed{\tau \to K}$

$|V_{us}|$ from tau measurements [HFLAV 2023 report]



$|V_{us}|_{\tau\text{-OPE}}$ uncertainty budget [%] ($|V_{us}|_{\tau\text{-latt}}$ is comparable)

$\pi^- \bar{K}^0 2\pi^0 \nu_\tau$ (ex. K^0)	0.3933
$K^- 2\pi^0 \nu_\tau$ (ex. K^0)	0.3789
$K^- 3\pi^0 \nu_\tau$ (ex. K^0, η)	0.3715
$\bar{K}^0 h^- h^- h^+ \nu_\tau$	0.3452
$K^- \pi^0 \nu_\tau$	0.2561
$K^- \pi^- \pi^+ \pi^0 \nu_\tau$ (ex. K^0, ω, η)	0.2438
$\pi^- \bar{K}^0 \nu_\tau$	0.2373
$\pi^- \bar{K}^0 \pi^0 \nu_\tau$	0.2201
$K^- \nu_\tau$	0.1646
$K^- \omega \nu_\tau$	0.1573
$K^- \nu_\tau$	0.1453
$K^- \pi^- \pi^+ \nu_\tau$ (ex. K^0, ω)	0.1148
$\pi^- \bar{K}^0 \eta \nu_\tau$	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
$K^- \phi \nu_\tau$ ($\phi \to K^0_S K^0_L$)	0.0094
$K^- 2\pi^- 2\pi^+ \nu_\tau$ (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
$\mathcal{B}_e^{\text{univ}}$	0.0044
theory	0.4863

- Belle II could improve measurements on large multiplicity strang tau decays
- lattice QCD may plausibly reduce the theory uncertainty

Uncertainty budget of $|V_{us}|$ with exclusive tau measurements

input	Δinput [%]	$\Delta\,|V_{us}|_{\tau K/\pi}$ [%]	$\Delta\,|V_{us}|_{\tau K}$ [%]
$\mathcal{B}(\tau^- \to K^- \nu_\tau)$		0.69	0.69
$\mathcal{B}(\tau^- \to \pi^- \nu_\tau)$		0.24	
$f_{K\pm}/f_{\pi\pm}$		0.16	
$f_{K\pm}$			0.19
S_{EW}^{τ}			0.02
$\delta R_{\tau K}$		0.28	0.29
$\delta R_{\tau\pi}$		0.28	
$|V_{ud}|$		0.03	
tau lifetime			0.09

- Belle II might improve tau branching fractions
- if $\Delta\mathcal{B}(\tau^- \to \pi^- \nu_\tau)$ reduced by ≥ 3, radiative corrections will be limiting
- lattice QCD may provide more precise radiative corrections in the future

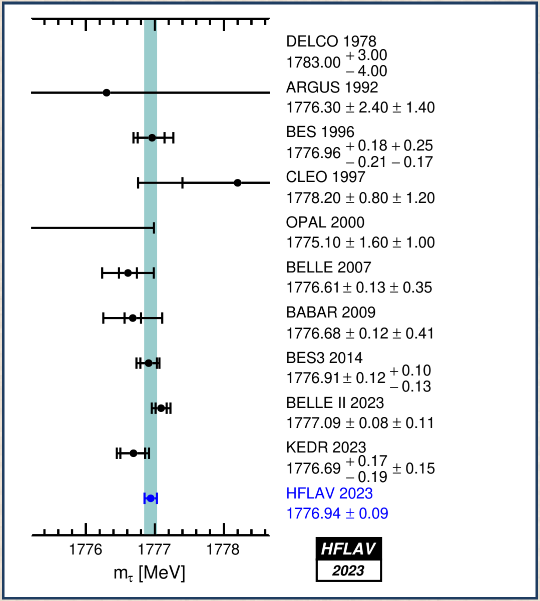
Summary

- improved HFLAV tau BR fir for HFLAV 2023 report (accepted by PRD, arXiv:2411.18639 [hep-ex])
- HFLAV tau BR fit results used to compute tau-related Lepton Flavour Universality tests
  - LO $\rightarrow$ NLO QED radiative corrections (first presented here, not included in HFLAV 2023 report)
- HFLAV tau BR fit results used to compute $|V_{us}|$
  - added new $|V_{us}|$ calculation relying on recent lattice QCD calculation

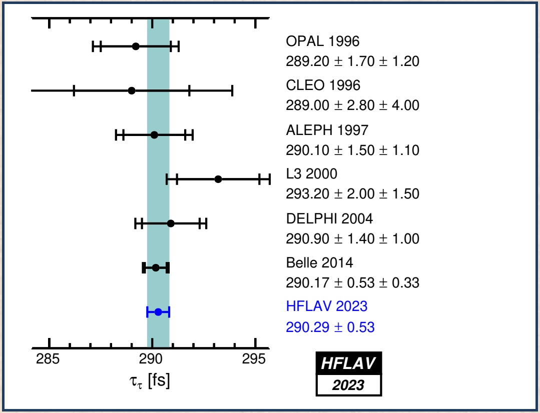
End

Backup slides

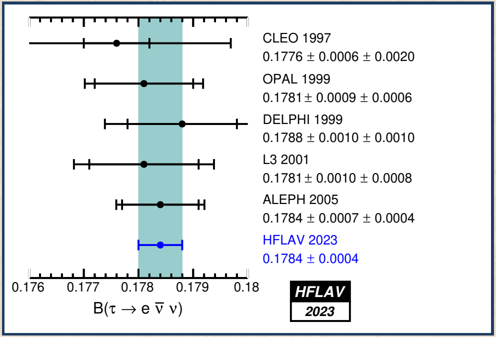
HFLAV Tau mass measurements

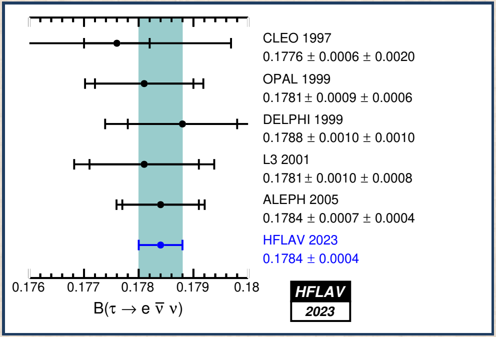


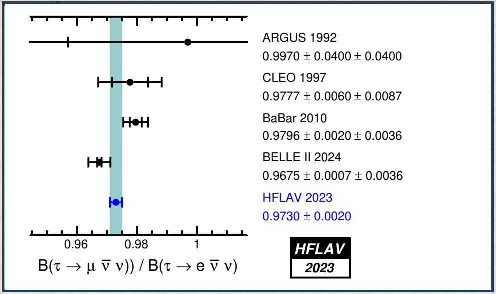
HFLAV Tau lifetime measurements



HFLAV Tau branching fractions measurements



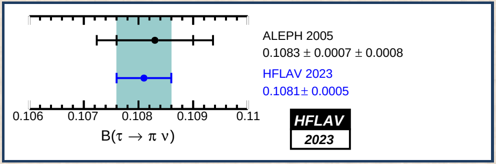


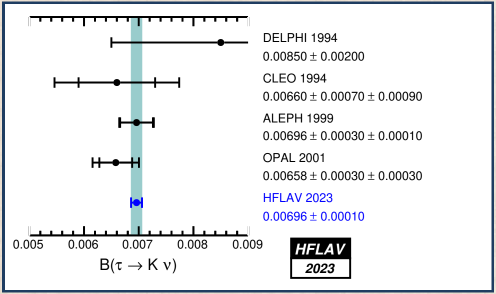


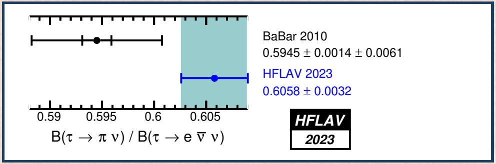
$|V_{us}|$ determinations from kaons

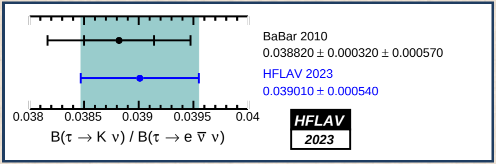
- $\Gamma(K \to \pi \ell \bar{\nu}_\ell[\gamma]) = \frac{G_F^2 m_K^5}{192\pi^3} C_K^2 \, S_{\text{EW}}^K \left(|V_{us}| f_+^{K\pi}(0) \right)^2 I_K^\ell \left(1 + \delta_{\text{EM}}^{K\ell} + \delta_{\text{SU(2)}}^{K\pi}\right)^2$ $K_{\ell 3}$
  - C_K Clebsch-Gordan coefficients, $= 1$ for K^0, $= 1/2$ for K^-
  - $I_K^\ell =$ phase-space form factor integral
- $\frac{\Gamma(K^- \to \ell^- \bar{\nu}_\ell)}{\Gamma(\pi^- \to \ell^- \bar{\nu}_\ell)} = \frac{|V_{us}|^2}{|V_{ud}|^2} \left(\frac{f^{K\pm}}{f^{\pi\pm}} \right)^2 \frac{m_K(1 - m_\ell^2/m_K^2)^2}{m_\pi(1 - m_\ell^2/m_\pi^2)^2} (1 + \delta_{\text{EM}})$ $K_{\ell 2}$

$\mathcal{B}(\tau^- \to \pi^- \nu_\tau)$ & $\mathcal{B}(\tau^- \to K^- \nu_\tau)$ measurements









μ/e universality from $\mathcal{B}(\pi \to e\nu(\gamma))/\mathcal{B}(\pi \to \mu\nu(\gamma))$

- $R^{\pi}_{e/\mu,\ \mathrm{SM}} = 1.23524(15)\cdot 10^{-4}$
- $R^{\pi}_{e/\mu,\ \mathrm{PIENU(2015)}} = 1.2344(23)\mathrm{stat}(19)\mathrm{syst}\cdot 10^{-4}$ PRL 115 (2015) 071801
- $R^{\pi}_{e/\mu,\ \mathrm{EXP}} = 1.2327(23)\cdot 10^{-4}$ PDG 2024
- on-going PEN experiment at PSI also aims to measure $R^{\pi}_{e/\mu}$
- future: PIONEER (PSI) uncertainty goal equal to SM prediction precision