Status of charged lepton flavour violation searches and lepton universality tests

Alberto Lusiani
Scuola Normale Superiore and INFN, sezione di Pisa

4th Workshop on Muon Precision Physics 2025 (MPP2025)
Liverpool, 11-13 November 2025

Introduction

Lepton flavour violation (LFV)

- Standard Model accidental symmetry conserves L_e, L_μ, L_τ
- νSM (including neutrino mixing) predicts extremely suppressed charged Lepton Flavour Violation, ($\propto m^2_{\nu_i}/m^2_W$), e.g., $\mathcal{B}(\mu \to e\gamma) \sim 10^{-54}$
  $\Rightarrow$ can do clean searches for New Physics
- LFV processes
  - muon LFV decays
  - tau LFV decays
  - hadrons, W/Z, H decays to leptons

Lepton flavour universality (LFU)

- Standard Model predicts universal couplings for leptons with only exception of Higgs Yukawa couplings
- most tested:
  charged-weak-current couplings universality
- precise SM predictions of coupling ratios
  $\Rightarrow$ can search for small NP deviations
  $\Rightarrow$ can obtain constraints on NP models
- lepton universality tests related to
  - B anomalies (R_D, R_{D^*}, R_K, R^*_K, ...)
  - Cabibbo angle anomaly

main recent updates

- new results of MEG-II search for $\mu \to e\gamma$
- Belle II searches on LFV tau decays
- Belle II measurements of tau mass and $\mathcal{B}(\tau \to \mu\bar{\nu}\nu)/\mathcal{B}(\tau \to e\bar{\nu}\nu)$
- updated information on future sensitivites from inputs to ESPPU 2025

Lepton Flavour Violation

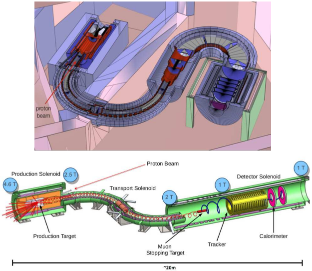
LFV processes selected experimental searches

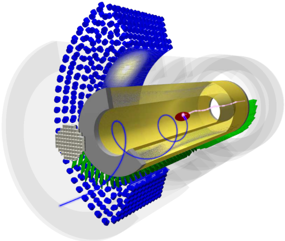
process	current bound on BR	estimated future sensitivity
$\mu \to e\gamma$	$< 1.5 \cdot 10^{-13}$ (MEG II)	$< 6 \cdot 10^{-14}$ (MEG II Phase II, $\sim$2026)
$\mu \to eee$	$< 1 \cdot 10^{-12}$ (SINDRUM)	$< 2.3 \cdot 10^{-16}$ (Mu3e, $>$2028)
$\mu \to e$	$< 7.0 \cdot 10^{-13}$ (SINDRUM II, Au)	$< 6.9 \cdot 10^{-17}$ (Mu2e Run II)
$\tau \to e\gamma$	$< 3.3 \cdot 10^{-8}$ (BaBar)	$< 1 \cdot 10^{-9}$ (Belle II, $50\,\text{ab}^{-1}$)
$\tau \to \mu\gamma$	$< 4.2 \cdot 10^{-8}$ (Belle)	$< 7 \cdot 10^{-9}$ (Belle II, $50\,\text{ab}^{-1}$)
$\tau \to \mu\mu\mu$	$< 2.1 \cdot 10^{-8}$ (Belle)	$< 5.8 \cdot 10^{-10}$ (Belle II avg, $50\,\text{ab}^{-1}$)
$Z \to e\mu$	$< 2.6 \cdot 10^{-7}$ (ATLAS)	$< 1.0 \cdot 10^{-9}$ (FCC)
$Z \to e\tau$	$< 5.0 \cdot 10^{-6}$ (ATLAS)	$< 1.0 \cdot 10^{-9}$ (FCC)
$Z \to \mu\tau$	$< 6.5 \cdot 10^{-6}$ (ATLAS)	$< 1.0 \cdot 10^{-9}$ (FCC)
$H \to e\mu$	$< 4.4 \cdot 10^{-5}$ (CMS)	$< 1.2 \cdot 10^{-5}$ (FCC)
$H \to e\tau$	$< 2.0 \cdot 10^{-3}$ (ATLAS)	$< 1.6 \cdot 10^{-4}$ (FCC)
$H \to \mu\tau$	$< 1.5 \cdot 10^{-3}$ (CMS)	$< 1.4 \cdot 10^{-4}$ (FCC)

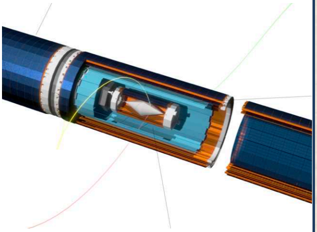
- omitted hadron LFV decays (limited time, less central to topic)
- limits are 90% or 95% C.L.
- converted SES into 90% C.L. limit $= 2.3 \times$ SES, assuming negligible background

Muon CLFV experiments

$\mu^- N \to e^- N$	$\mu^+ \to e^+ \gamma$	$\mu^+ \to e^+ e^- e^+$







[T.Mori, ICHEP 2022]

- key element availability of intense muon sources
- low energy high resolution detectors (also in time)
- special care to suppress beam related and other backgrounds

Muon CLFV experiments

$\mu^- N \to e^- N$

- signal: monochromatic ~104MeV electron
- BG: beam-related prompt
- pulsed muon beam
- "extinction" of ~10^{-10}
- low mass tracker

$\mu^+ \to e^+ \gamma$

- signal: 2-body kinematics
- BG: accidental
- DC muon beam
- low mass tracker
- excellent gamma-ray measurement

$\mu^+ \to e^+ e^- e^+$

- signal: 3-body kinematics
- BG: accidental
- DC muon beam
- low mass tracker

[T.Mori, ICHEP 2022]

Muon CLFV experiments

$\mu^- N \to e^- N$

COMET & Mu2e

π capture and π, μ transport by solenoids

- prompt
- pulsed muon b
- "extinction" of
- low mass tracker

$\mu^+ \to e^+ \gamma$

MEG II

gradient field spectrometer & LXe photon detector

- DC muon beam
- excellent gamma-ray measurement

$\mu^+ \to e^+ e^- e^+$

Mu3e

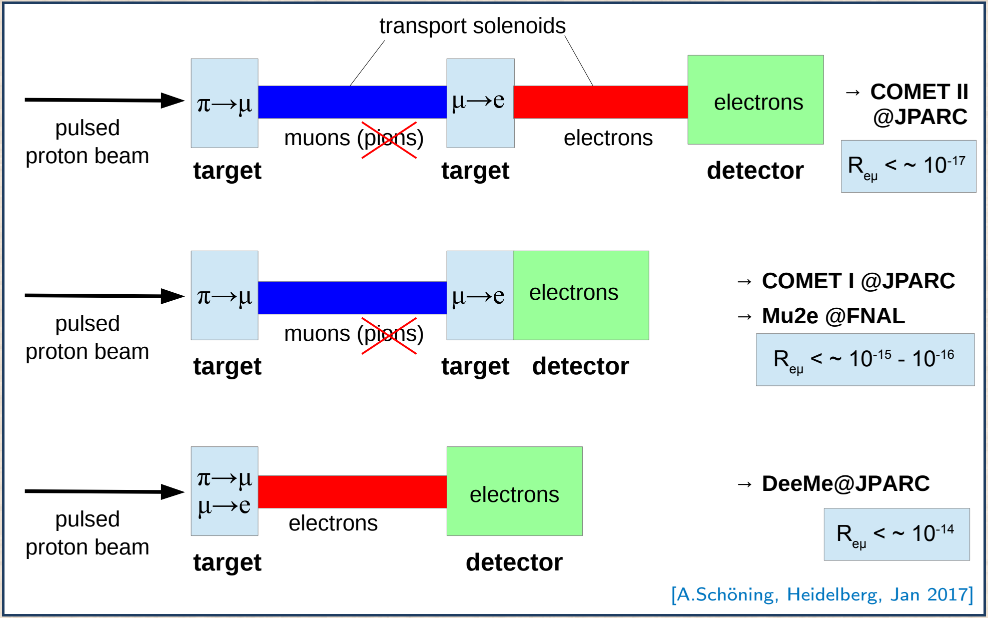
low mass pixel tracker based on HV-MAPS

- BG: accidental
- n beam
- s tracker

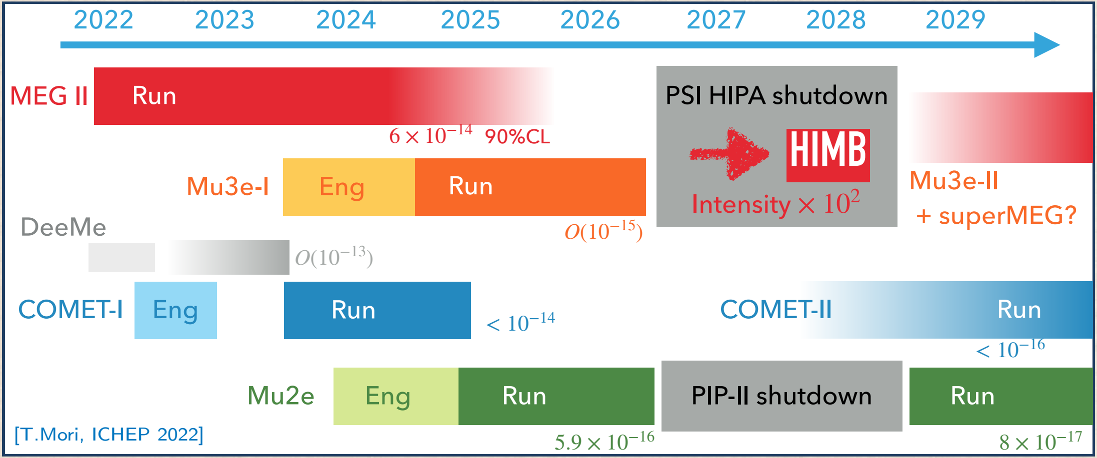
INNOVATIVE EXPERIMENTAL TECHNIQUES ARE DRIVING FORCE

[T.Mori, ICHEP 2022]

Searches for muon conversion in nuclei, techniques



Timeline of muon CLFV experiments

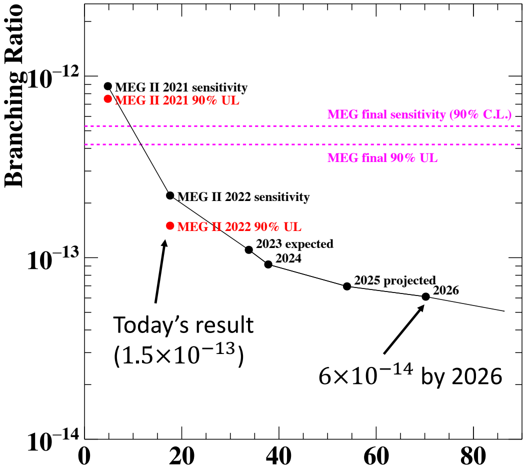


updates

- PSI HIPA shutdown starts Jan 2027
- FNAL PIP-II shutdown starts Jan 2028, Mu2e Run-I in 2027
- COMET Phase-I 2027-2029 ($1{\cdot}10^{-15}$ SES), Phase-II >2029 ($1{\cdot}10^{-17}$ SES)

MEG-II results and prospects on $\mathcal{B}(\mu \to e\gamma)$ 90% CL UL

- $<4.2{\cdot}10^{-13}$ MEG final (2016)
- $<7.5{\cdot}10^{-13}$ 2021, pub.
- $<1.5{\cdot}10^{-13}$ 2021+2022, EPJC 85 (2025) 10, 1177



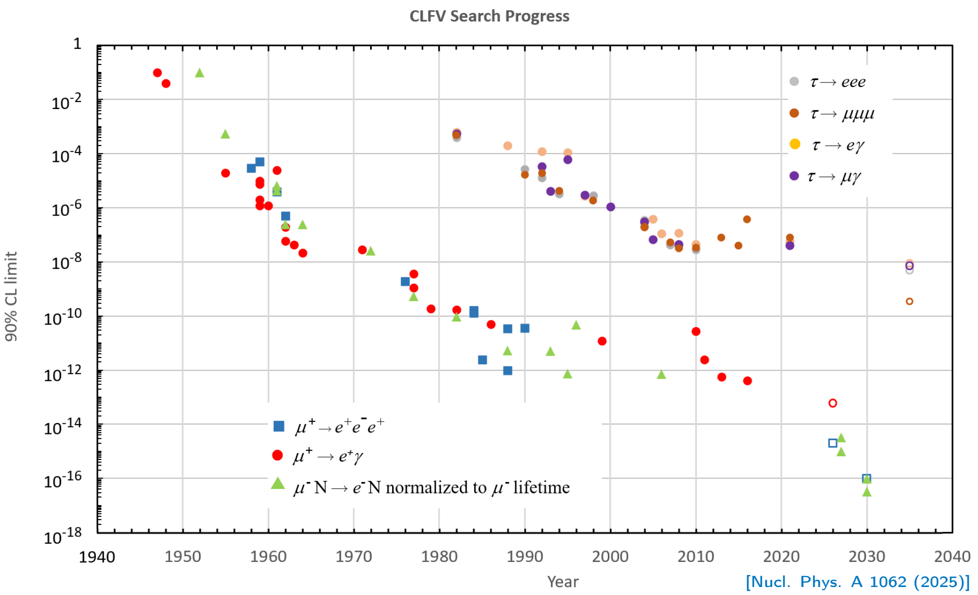
[Atsushi Oya, EPS2025]

MEG-II vs. MEG detector performances

	Δp_{e^+}	$\Delta\theta_{e^+}$	ΔE_γ	$\Delta\vec{x}$	$\Delta t_{e\gamma}$	ε_{e^+}	ε_γ
MEG	380 keV	9.4 mrad	2.4%/1.7%	5 mm	122 ps	30%	63%
MEG II (21)	89 keV	7.2 mrad	2.0%/1.8%	2.5mm	78 ps	67%	62%
MEG II (22)	79 keV	6.2 mrad	TBD	2.5 mm	TBD	67%	62%

[L.Gerritzen, Sep 2024]

Muon LFV searches status and prospects



[Nucl. Phys. A 1062 (2025)]

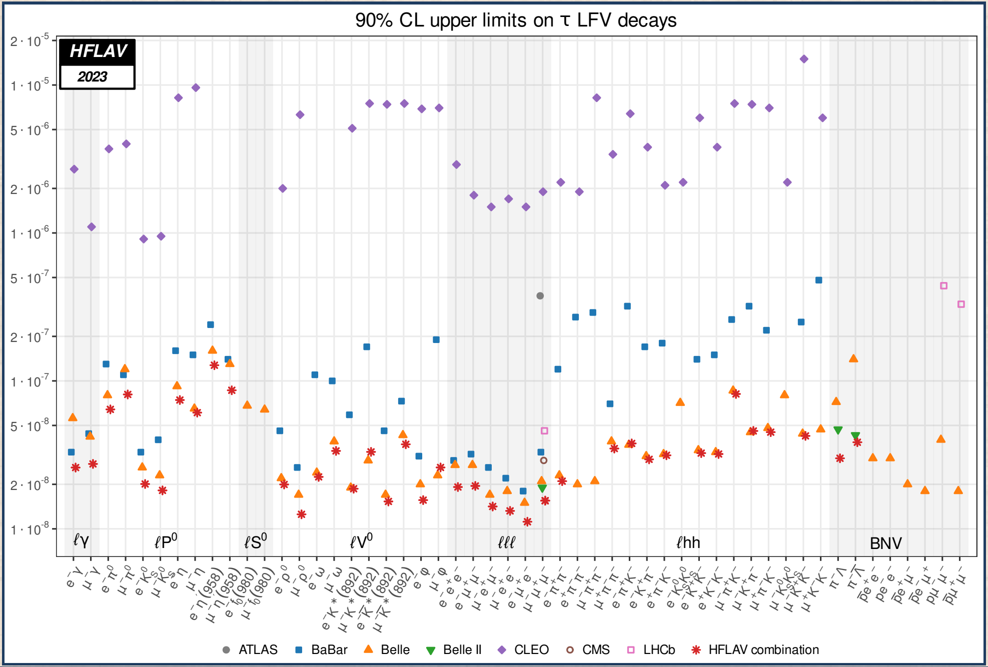
Searches for LFV in tau decays

- present upper limits mainly from CLEO, *BaBar*, Belle
- LHCb, CMS and ATLAS performed searches on $\tau^- \to \mu^-\mu^+\mu^-$, $\tau^- \to \bar{p}\mu^+\mu^-$
- Belle II will significantly improve B-factories limits
- possible future players FCC-ee(Z), CEPC, STCF

new Belle II limit on $\tau^- \to \mu^-\mu^+\mu^-$

- $\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 1.9{\cdot}10^{-8}$ JHEP 09 (2024) 062, 424 fb^{-1}
- previous $\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 2.1{\cdot}10^{-8}$ 90% CL, Phys.Lett.B687 (2010) 139-143, 782 fb^{-1}

Tau LFV decay upper limits and their combinations



Facilities for tau lepton measurements

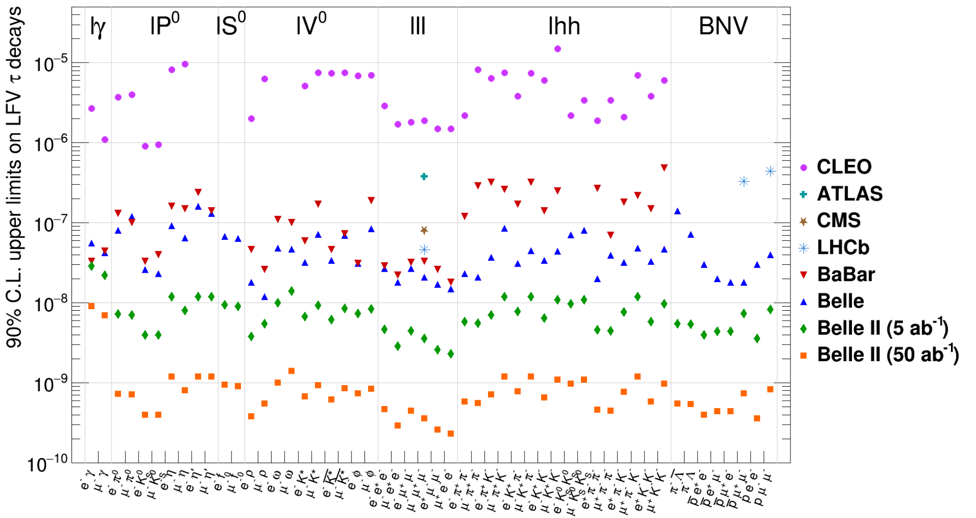
tau pairs yields at past, present and future e^+e^- colliders

facility	Z [million]	$\tau^+\tau^-$ [million]	$\tau^+\tau^-$ relative sample size	
LEP	25	0.84		
BaBar	-	$0.5{\cdot}10^3$		
Belle	-	$1.0{\cdot}10^3$		
Belle II	-	$45{\cdot}10^3$		
STCF at 4.26 GeV, 10 years	-	$35{\cdot}10^3$		
CEPC	$4{\cdot}10^6$	$135{\cdot}10^3$	$1.6{\cdot}10^5\times$LEP	$3.0\times$Belle II
FCC-ee	$6{\cdot}10^6$	$200{\cdot}10^3$	$2.4{\cdot}10^5\times$LEP	$4.5\times$Belle II

experimental conditions of tau pairs much better at Z peak compared to lower energies

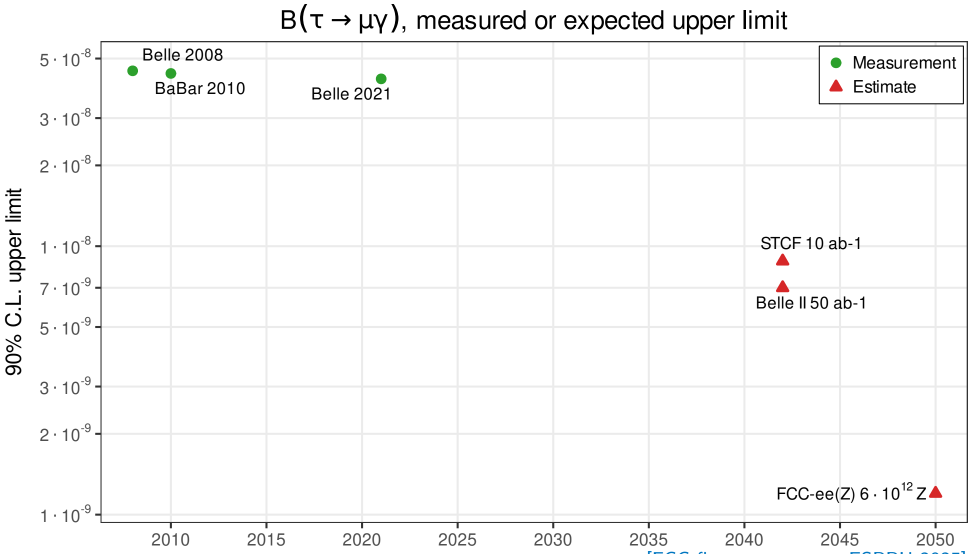
- better momentum resolution and vertexing because less multiple scattering with higher track momenta
- better higher momentum muon id (much lower pion-to-muon misidentification)
- much better $\tau^+\tau^-$ separation from $q\bar{q}$ background because of higher $q\bar{q}$ multiplicity at Z peak
- LHC produces more tau leptons, but with much less favourable experimental conditions

Belle II expected tau LFV decay upper limits



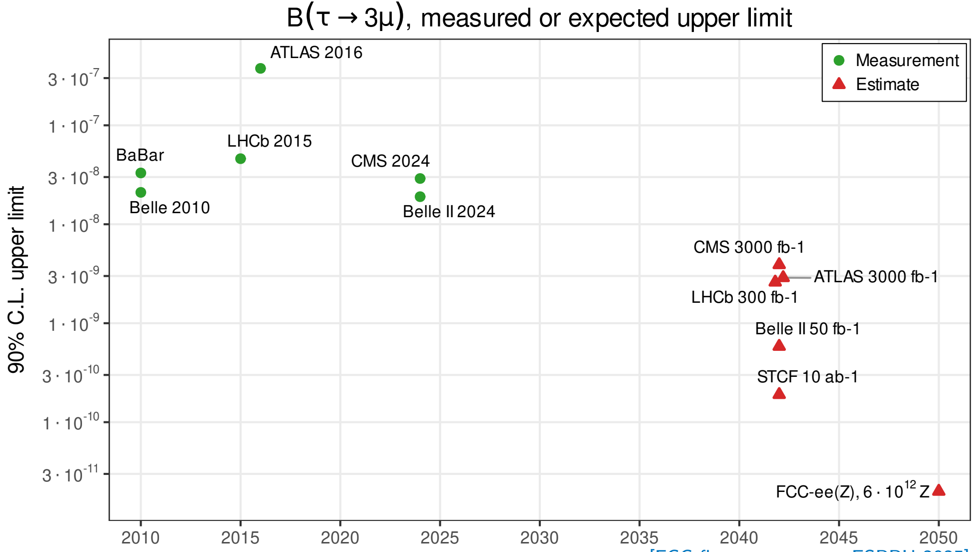
[Snowmass 2021 White Paper: Charged lepton flavor violation in the tau sector]

LFV search for $\tau \to \mu\gamma$



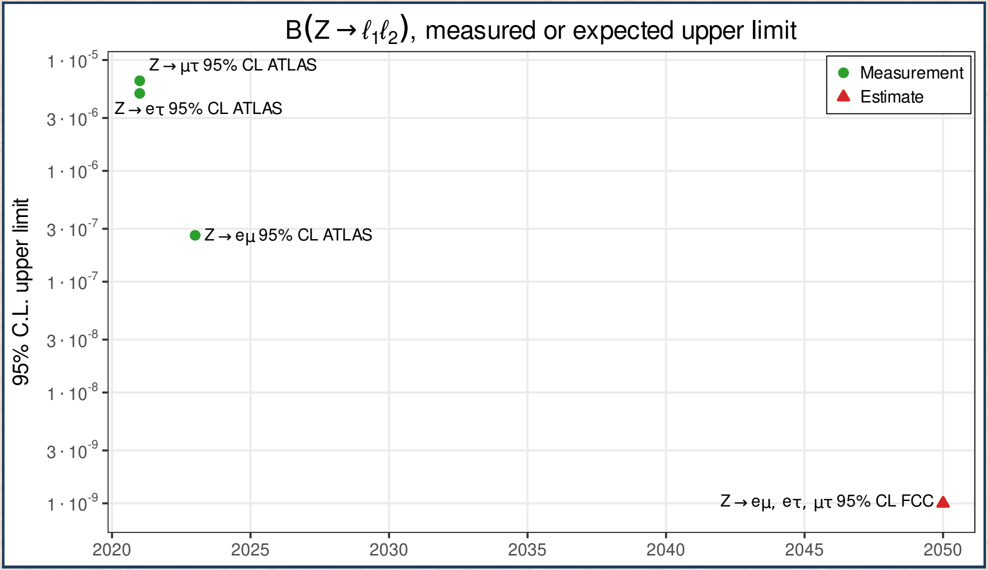
[FCC flavour prospects ESPPU 2025]

LFV search for $\tau \to 3\mu$

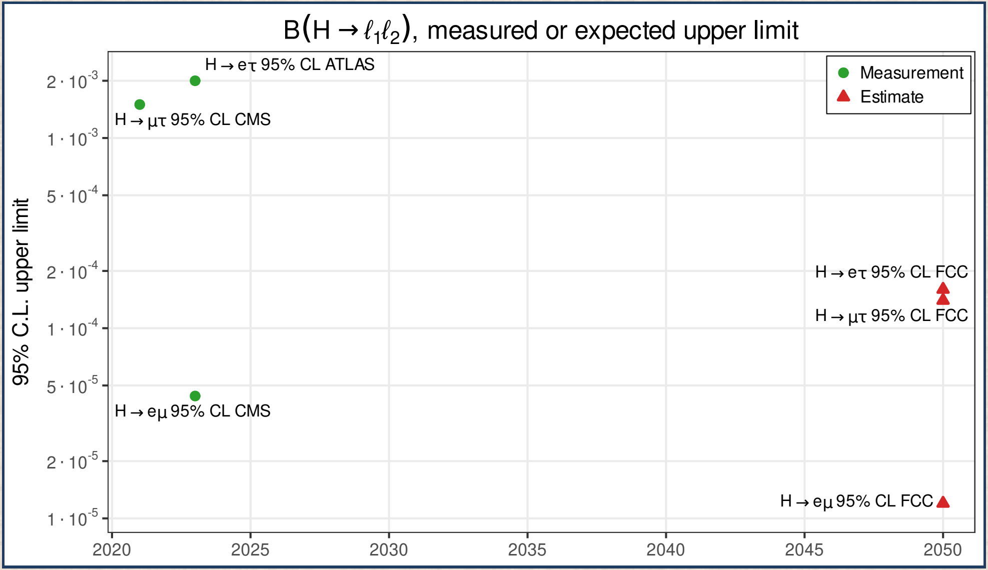


[FCC flavour prospects ESPPU 2025]

LFV search for $Z \to \ell_1\ell_2$



LFV search for $H \to \ell_1\ell_2$



Lepton flavour universality

Experimental tests of lepton flavour universality

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

$\lvert g_\mu/g_e \rvert$	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$ 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)	$\Gamma_{K\to\pi\mu}/\Gamma_{K\tau\to\pi e}$ 1.0010(25)	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$ 0.996(10)
$\lvert g_\tau/g_\mu \rvert$	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$ 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)
$\lvert g_\tau/g_e \rvert$	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$ 1.0030(15)				$\Gamma_{W\to\tau}/\Gamma_{W\to e}$ 1.031(13)

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

$\lvert g_\mu/g_e \rvert$	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$ 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)	$\Gamma_{K\to\pi\mu}/\Gamma_{K\tau\to\pi e}$ 1.0009(18)	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$ 1.001(3)
$\lvert g_\tau/g_\mu \rvert$	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$ 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)
$\lvert g_\tau/g_e \rvert$	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$ 1.0018(14)				$\Gamma_{W\to\tau}/\Gamma_{W\to e}$ 1.008(10)

Lepton universality tests

today status [HFLAV 2023 report]

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

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

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

using Standard Model predictions for leptons $\mathcal{L}$, $\ell = e, \mu, \tau$ (Marciano, 1988):

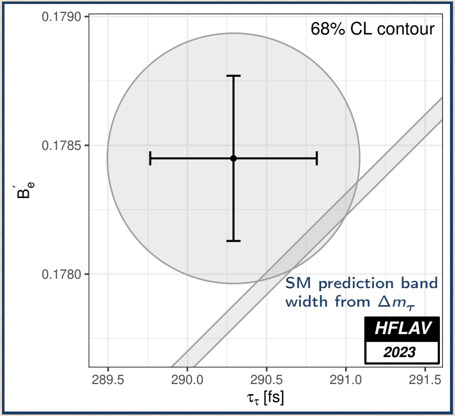
$$\Gamma[\mathcal{L} \to \nu_{\mathcal{L}} \ell \bar{\nu}_\ell(\gamma)] = \Gamma_{\mathcal{L}\ell} = \Gamma_{\mathcal{L}} \mathcal{B}_{\mathcal{L}\ell} = \frac{\mathcal{B}_{\mathcal{L}\ell}}{\tau_{\mathcal{L}}} = \frac{G_{\mathcal{L}} G_\ell m_{\mathcal{L}}^5}{192\pi^3} f\left(m_\ell^2/m_{\mathcal{L}}^2\right) R_W^{\mathcal{L}} R_\gamma^{\mathcal{L}}$$

$$G_{\mathcal{L}} = \frac{g_{\mathcal{L}}^2}{4\sqrt{2} M_W^2} ; \qquad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x ; \qquad f_{\mathcal{L}\ell} = f\left(m_\ell^2/m_{\mathcal{L}}^2\right)$$

$$R_W^{\mathcal{L}\ell} = 1 + \frac{3}{5}\frac{m_{\mathcal{L}}^2}{M_W^2} + \frac{9}{5}\frac{m_\ell^2}{M_W^2} ; \qquad R_\gamma^{\mathcal{L}} = 1 + \frac{\alpha(m_{\mathcal{L}})}{2\pi}\left(\frac{25}{4} - \pi^2\right) ;$$ all statistical correlations included

- less precise tests possible with hadronic tau decays
- tau BF, mass, lifetime from HFLAV tau averages

Canonical tau lepton universality test plot



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

[HFLAV 2023]

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

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

Tau - muon universality using tau hadronic branching fractions

$$\left(\frac{g_\tau}{g_\mu}\right)^2_h = \frac{\mathcal{B}(\tau \to h\nu_\tau)}{\mathcal{B}(h \to \mu\bar{\nu}_\mu)} \frac{2m_h m_\mu^2 \tau_h}{(1+\delta R_{\tau/h}) m_\tau^3 \tau_\tau} \left(\frac{1-m_\mu^2/m_h^2}{1-m_h^2/m_\tau^2}\right)^2 ,$$

- $h = \pi$ or K
- $\delta R_{\tau/\pi} = (0.18 \pm 0.57)\%$ [PhysRevD.104.L091502 (2021)]
- $\delta R_{\tau/K} = (0.97 \pm 0.58)\%$ [PhysRevD.104.L091502 (2021)]
- tau BF from HFLAV tau averages

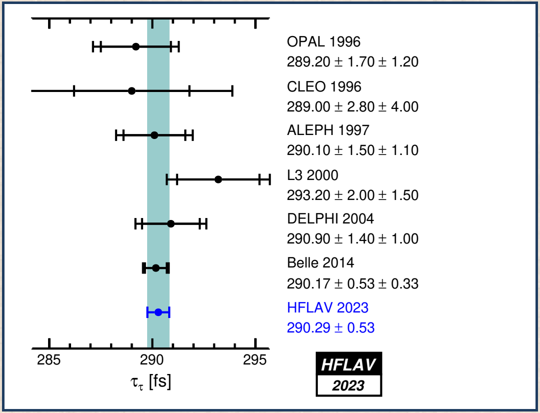
$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 0.996 \pm 0.004 , \qquad \left(\frac{g_\tau}{g_\mu}\right)_K = 0.986 \pm 0.008 .$$

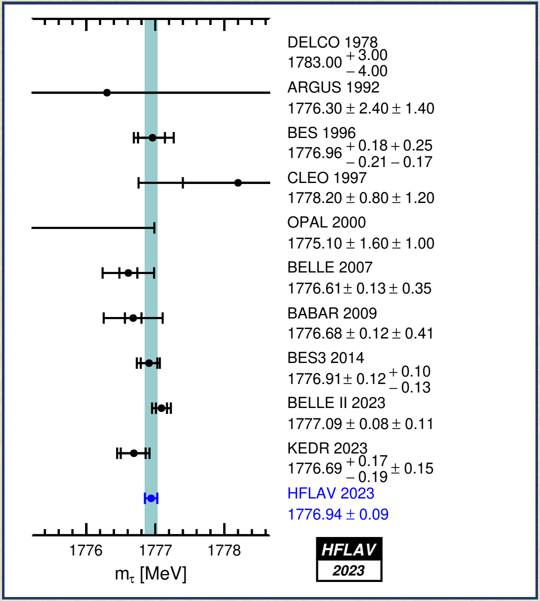
- $\mathcal{B}(\pi \to \mu\bar{\nu}_\mu)$, $\mathcal{B}(K \to \mu\bar{\nu}_\mu)$ PDG 2023

$$\left(\frac{g_\tau}{g_\mu}\right)_{\tau+\pi+K} = 1.0011 \pm 0.0014 , \tag{1}$$

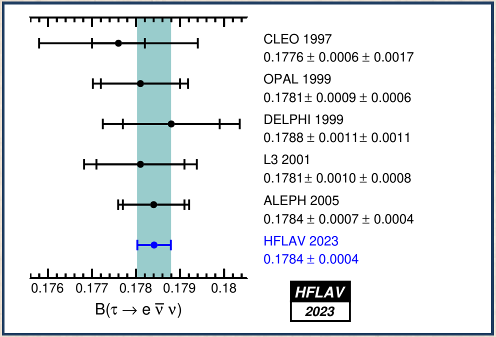
- average of three tau vs. mu universality tests
- assuming uncorrelated $\delta R_{\tau/\pi}$ and $\delta R_{\tau/K}$

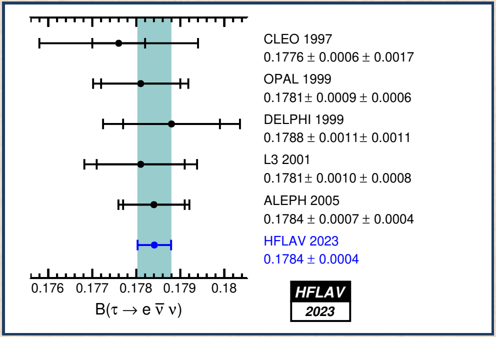
Tau mass and lifetime measurements

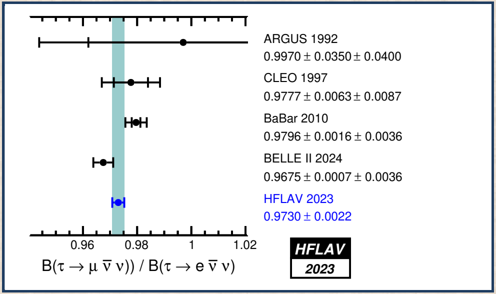




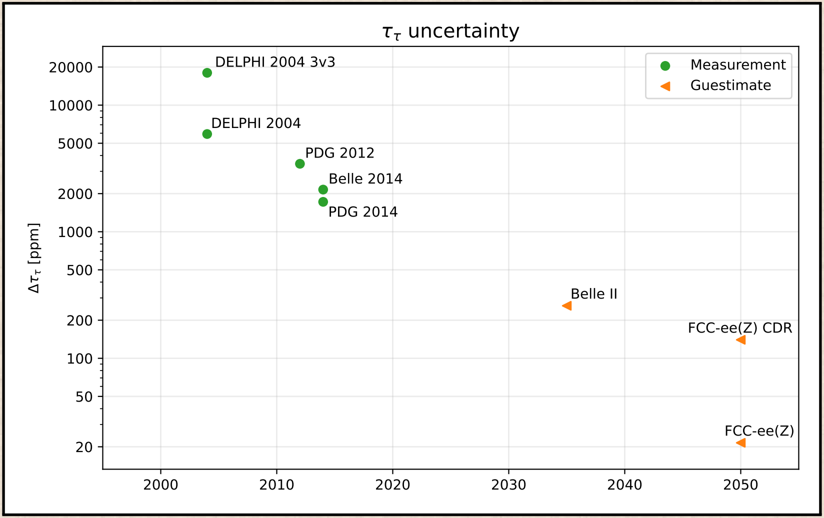
Tau branching fractions measurements





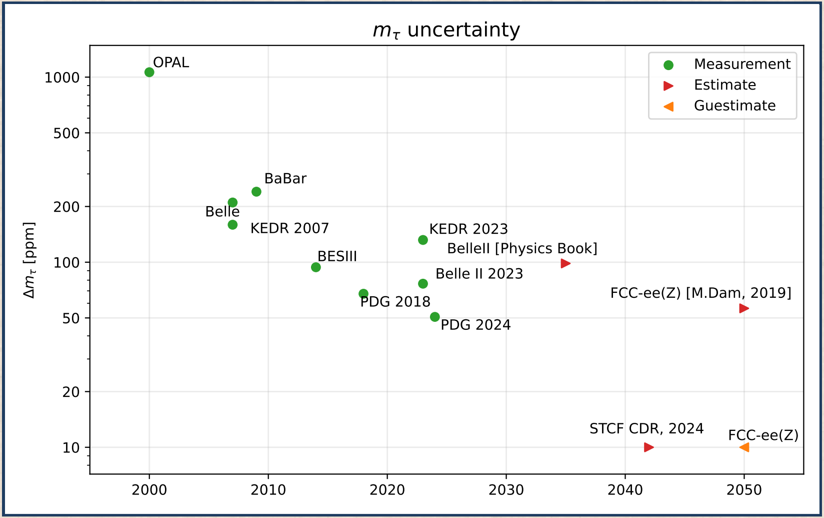


Tau Lifetime measurement prospects



FCC-ee(Z) with $6{\cdot}10^{12}$ Z

Tau mass measurement prospects

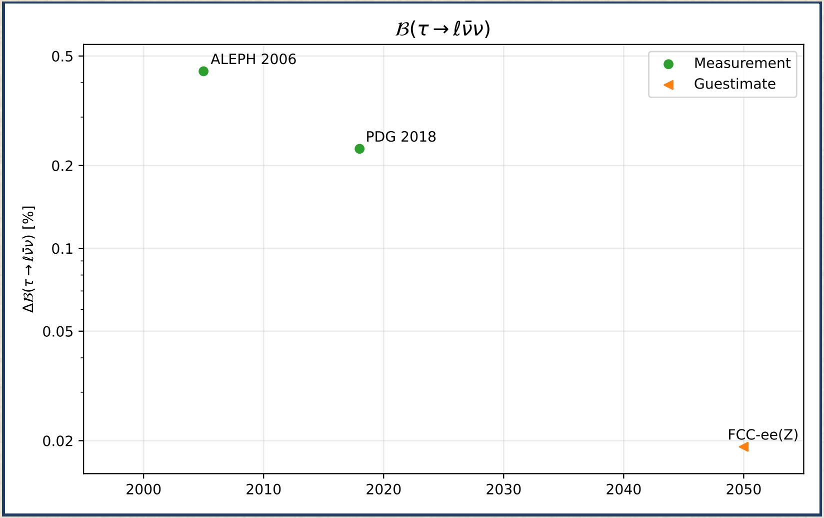


FCC-ee(Z) with $6{\cdot}10^{12}$ Z

Tau leptonic branching fractions measurement prospects

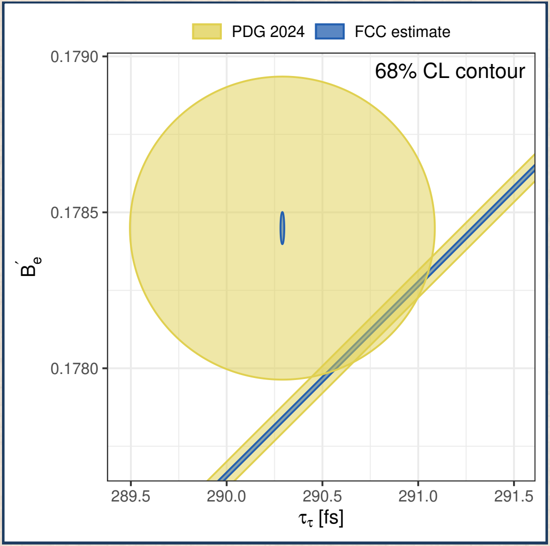
- ALEPH 2006 measurement precision: $4400\,\text{ppm} = [4000(\text{stat.}) \oplus 1900(\text{syst.})]\,\text{ppm}$
  (average of the two similar electron and muon decays branching fractions)
  - complex simultaneous measurement of 12 tau branching fractions
  - many systematic uncertainties, no reliable extrapolations to FCC-ee statistics
  - several systematics related to photon and $\pi^0 \to \gamma\gamma$ reconstruction
- $\Delta^{\text{FCC}}_{\text{stat}}\mathcal{B}(\tau \to \ell\bar{\nu}\nu) = 4000\,\text{ppm} \cdot \sqrt{\dfrac{6.2{\cdot}10^6\ \text{(ALEPH Z bosons)}}{6{\cdot}10^{12}}} = 4.1\,\text{ppm}\ \text{(FCC Z bosons)}$
- $\Delta^{\text{FCC}}_{\text{syst}}\mathcal{B}(\tau \to \ell\bar{\nu}\nu) = \dfrac{1}{10} \cdot 1900\,\text{ppm} = 190\,\text{ppm}$
  [assume also 100% correlated between $\mathcal{B}(\tau \to e\bar{\nu}\nu)$ and $\mathcal{B}(\tau \to \mu\bar{\nu}\nu)$]
- $\Delta^{\text{FCC}}\mathcal{B}(\tau \to \ell\bar{\nu}\nu) \simeq 190\,\text{ppm}$

Tau leptonic Branching fractions prospects at FCC-ee and other facilities



- FCC-ee(Z) with $6{\cdot}10^{12}$ Z
- Belle II is working on these measurements

Canonical tau lepton universality plot extrapolation at FCC-ee



FCC-ee(Z) with $6{\cdot}10^{12}$ Z

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

Summary

- status and prospects of lepton flavour violation searches
- status and prospects of lepton flavour universality tests

End

Backup slides

Some references

- HFLAV 2023 report (accepted by PRD) arXiv:2411.18639 [hep-ex]

Searches for muon conversion in nuclei, $\mu N \to eN$

- DeeMe, C target, 1 year (JPARC, Japan), SES $\sim 1{\cdot}10^{-13}$
- DeeMe, SiC target, 4 years (JPARC, Japan), SES $\sim 5{\cdot}10^{-15}$
- Mu2e (FNAL, USA), SES $\sim 3{\cdot}10^{-17}$
- COMET-1 (JPARC, Japan), SES $\sim 3{\cdot}10^{-15}$
- COMET-2 (JPARC, Japan), SES $\sim 3{\cdot}10^{-17}$
- PRISM/PRIME (JPARC, Japan), SES $\sim 1{\cdot}10^{-18}$