Status of charged lepton flavour violation searches and lepton universality tests

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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

Lepton Flavour Violation

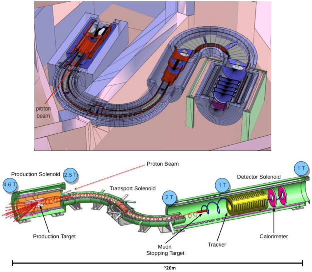
Esperimental searches for LFV processes

Process	Current bound on BR	Future Sensitivity
$\mu \to e\gamma$	$< 4.2 \times 10^{-13}$ MEG	10^{-14} MEGII
$\mu \to \bar{e}ee$	$< 1.0 \times 10^{-12}$ SINDRUM	10^{-16} Mu3e
$\mu A \to eA$	$< 7 \times 10^{-13}$ SINDRUMII	$10^{-16} \to 10^{-18}$ COMET, Mu2e
$\tau \to l\gamma$	$< 3.3 \times 10^{-8}$	$3 \times 10^{-9}(e), 10^{-9}(\mu)$
$\tau \to e\bar{e}e$	$< 2.7 \times 10^{-8}$	5×10^{-9}
$\tau \to \mu\bar{\mu}\mu$	$< 2.1 \times 10^{-8}$	4×10^{-9}
$\tau \to \mu\bar{e}e, e\bar{\mu}\mu$	$< 1.8, 2.7 \times 10^{-8}$ Belle	$3, 5 \times 10^{-9}$ BelleII
...	...	...
$\tau \to l\pi^0$	$< 8.0 \times 10^{-8}$	4×10^{-9}
$\tau \to l\eta$	$< 6.5 \times 10^{-8}$	7×10^{-9}
$\tau \to l\rho$	$< 1.2 \times 10^{-8}$ Belle	10^{-9} BelleII
$K^0 \to \mu^\pm e^\mp$	$< 4.7 \times 10^{-12}$	
$B_d^0 \to \tau^\pm\mu^\mp$	$< 1.2 \times 10^{-5}$ LHCb	$\sim 10^{-6}$?
...	...	...
$h \to e^\pm\mu^\mp$	$< 6.1 \times 10^{-5}$ Atlas	2.1×10^{-5}
$h \to e^\pm\tau^\mp$	$< 2.2 \times 10^{-3}$ CMS	2.4×10^{-4}
$h \to \tau^\pm\mu^\mp$	$< 1.5 \times 10^{-3}$ CMS	2.3×10^{-4} ILC
$Z \to e^\pm\mu^\mp$	$< 7.5 \times 10^{-7}$ Atlas	
$Z \to l^\pm\tau^\mp$	$< 10^{-7}$ Atlas	[M.Ardu, CLFV 2023]

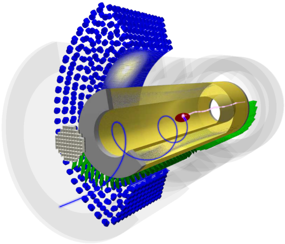
- muon searches most sensitive
- tau searches probe many operators can distinguish models
- W, Z, H, hadrons decays complementary

Muon CLFV experiments

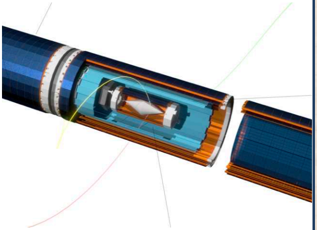
$\mu^- N \to e^- N$



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



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



[T.Mori, ICHEP 2022]

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

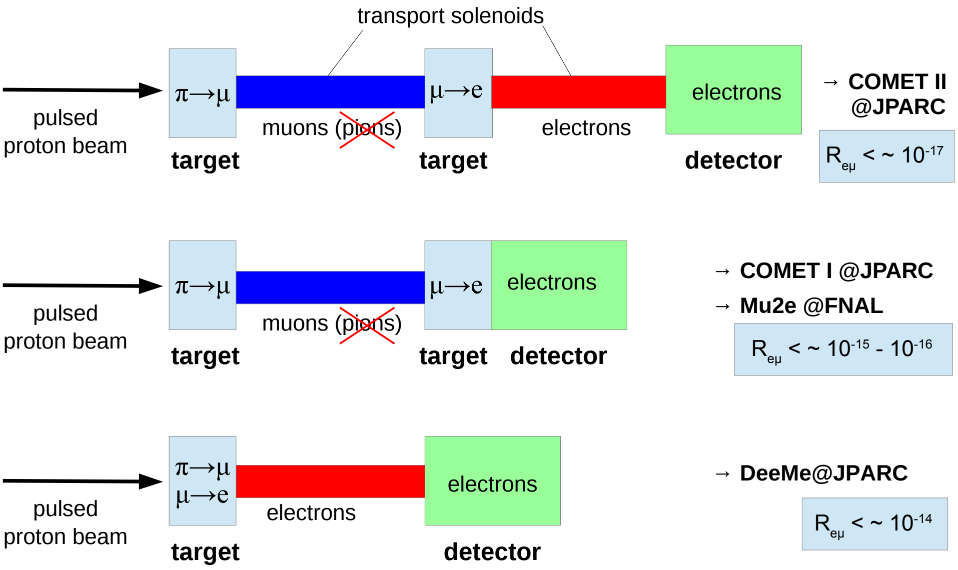
low mass pixel tracker based on HV-MAPS

- BG: accidental
- n beam
- s tracker

INNOVATIVE EXPERIMENTAL TECHNIQUES ARE DRIVING FORCE

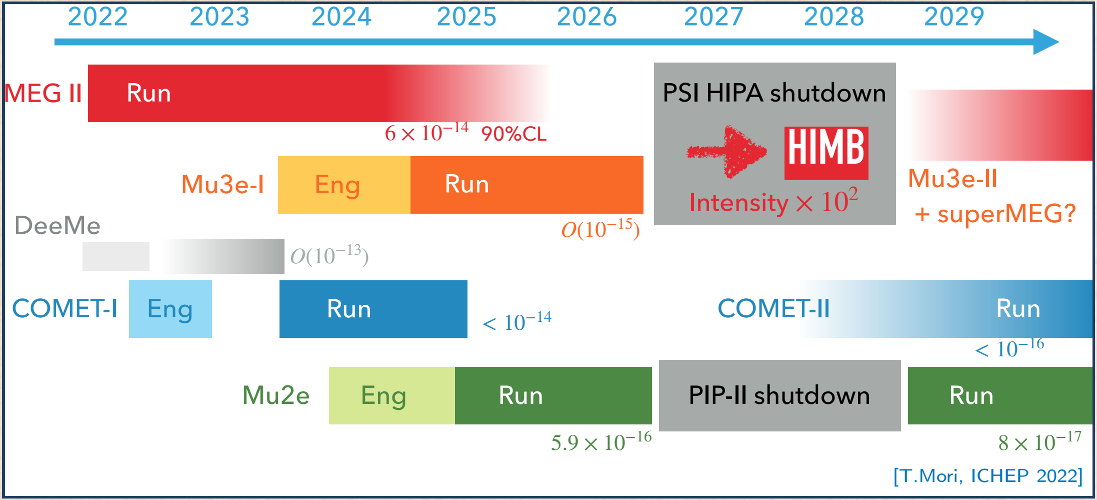
[T.Mori, ICHEP 2022]

Searches for muon conversion in nuclei, techniques

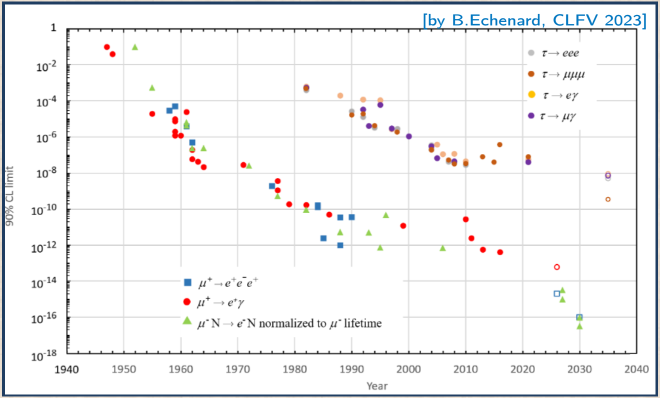


[A.Schöning, Heidelberg, Jan 2017]

Timeline of muon CLFV experiments



Muon LFV searches status and prospects



1st MEG-II search published

- MEG-II Run 1 (2021) search
  Euro.Phys.J.C 84 (2024) 3, 216
  $\mathcal{B}(\mu^+ \to e^+\gamma) < 7.5{\cdot}10^{-13}$ (90% CL)
- combined MEG 2016 + MEG-II 2024:
  $\mathcal{B}(\mu^+ \to e^+\gamma) < 3.1{\cdot}10^{-13}$ (90% CL)
- MEG 2016 final limit was:
  [$\mathcal{B}(\mu^+ \to e^+\gamma) <$
  $4.2{\cdot}10^{-13}$ (90% CL)]

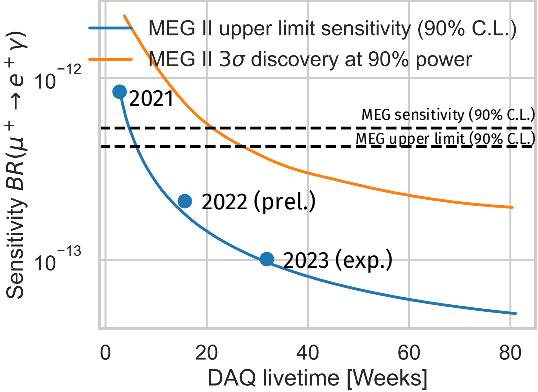
MEG-II vs. MEG detector performances

	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]

Future MEG + MEG-II sensitivity

- 2021 analysis published in January (no discovery)
- 2022 will follow soon
- 2023 dataset bigger than 2021+2022 combined
- 2024: likely short run
- 2025-2026: Ready to take data



[L.Gerritzen, Sep 2024]

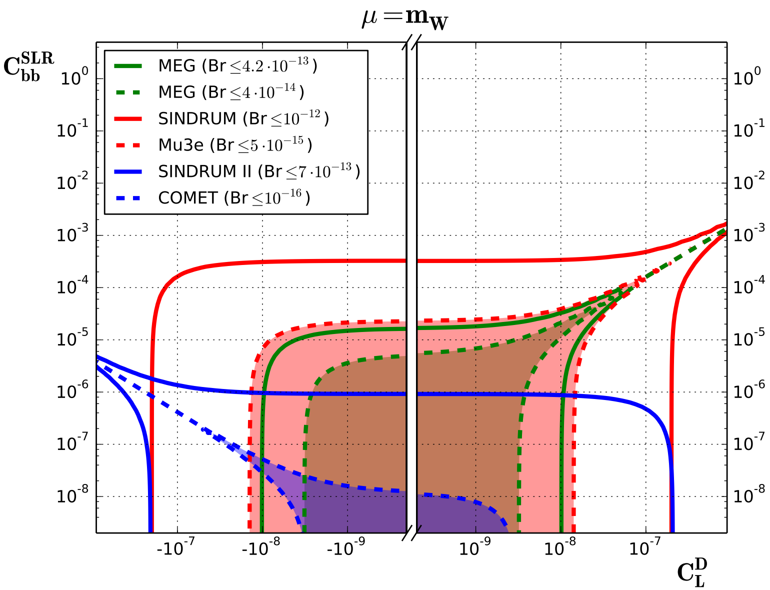
Comparison and complementarity of muon LFV searches

- model-independent parametrization of New Physics with SMEFT

$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \ldots$$

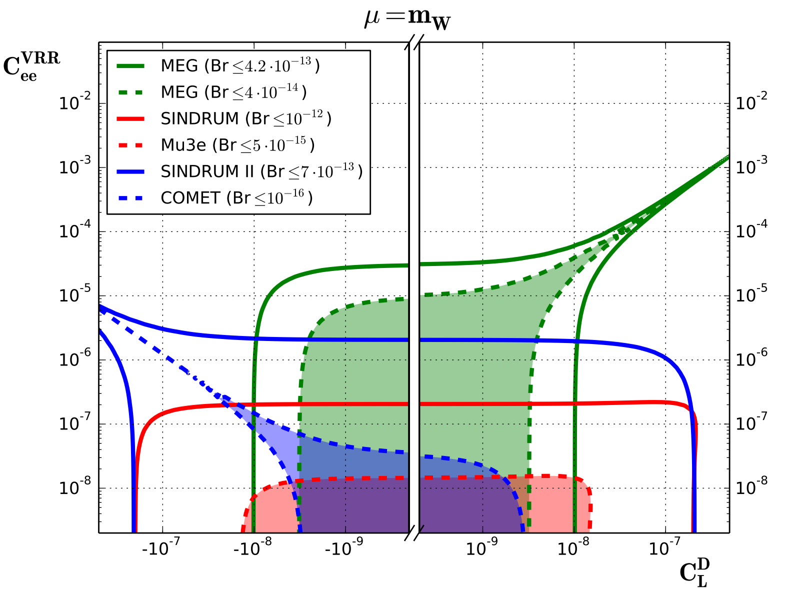
- scale-dependent Wilson coefficients (renormalization)
- use EW scale as reference to compare Wilson coefficients constraints from experimental measuremets at different energy scales

Comparison and complementarity of muon LFV searches



[A.Crivellin, S.Davidson, G.M.Pruna, A.Signer, JHEP 05 (2017) 117]

Comparison and complementarity of muon LFV searches



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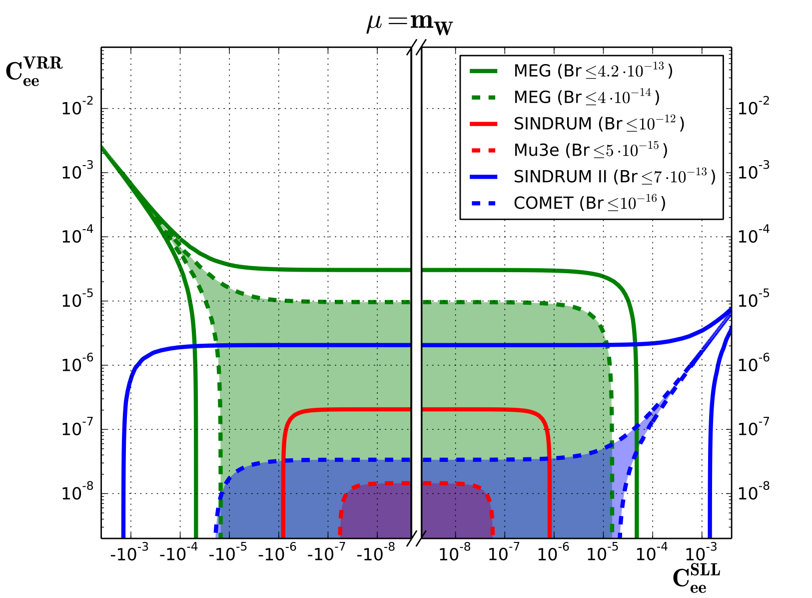

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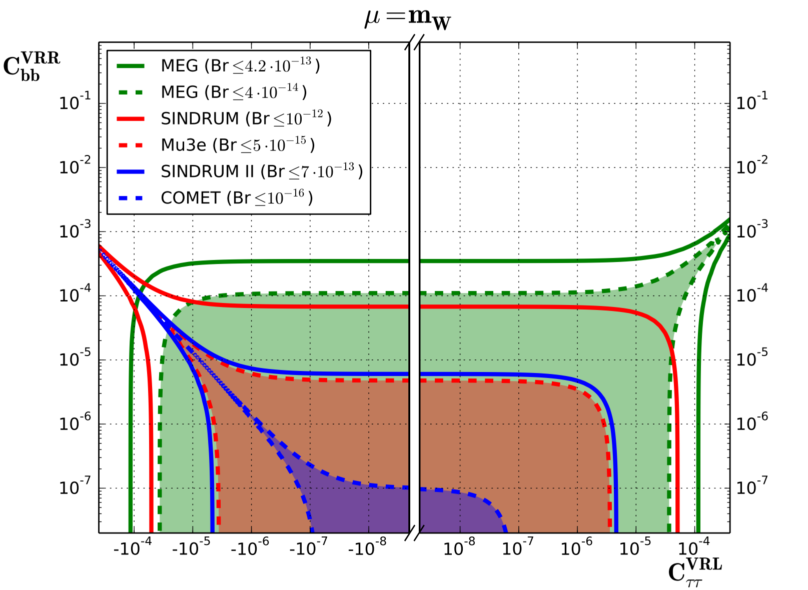


[A.Crivellin, S.Davidson, G.M.Pruna, A.Signer, JHEP 05 (2017) 117]

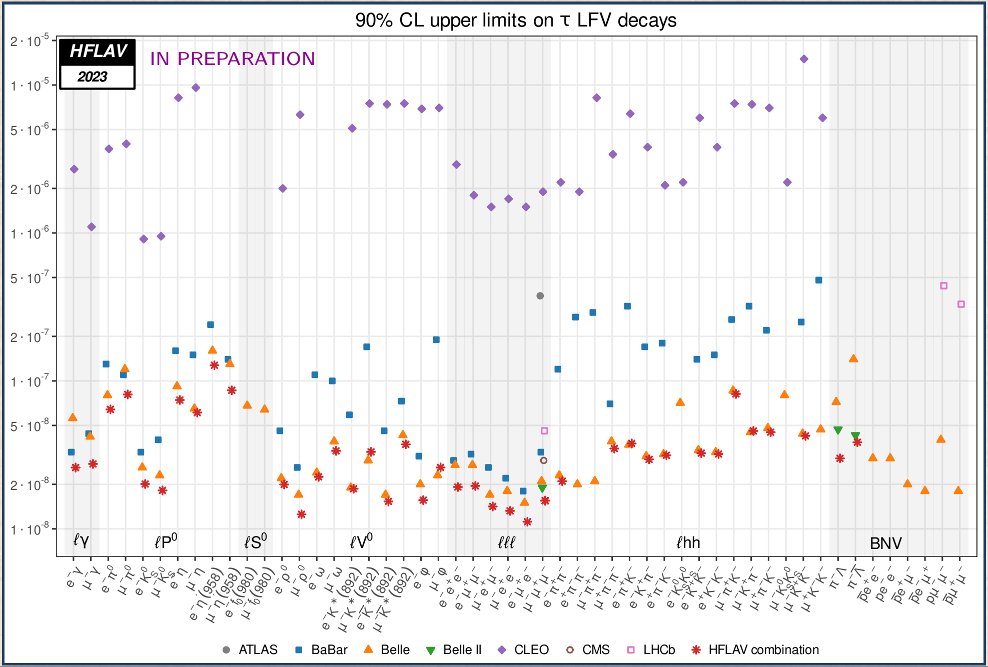
Searches for LFV in tau decays

- 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



Facilities for tau lepton measurements

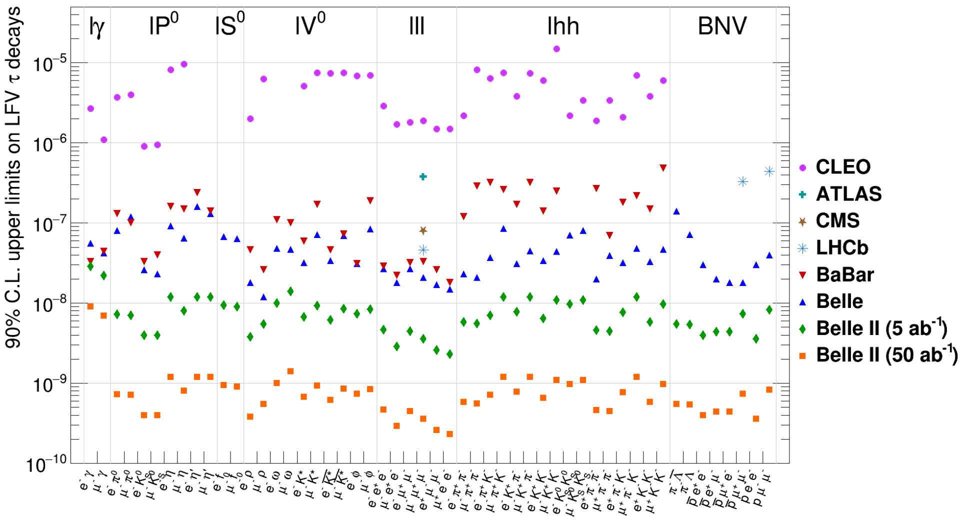
tau pairs yields at past, present and future e^+e^- colliders

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

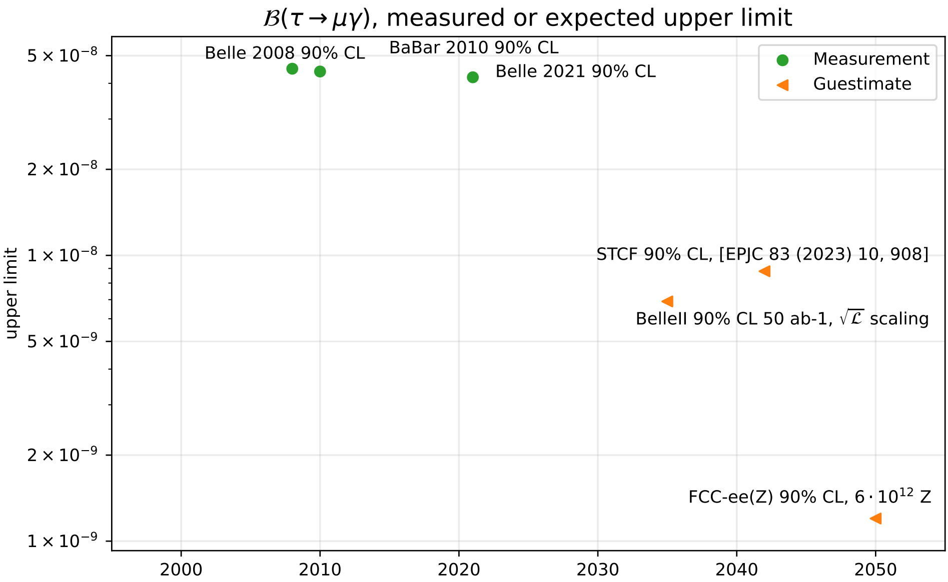
- better momentum resolution and vertexing because less multiple scattering with higher track momenta
- better higher momentum muon id (much lower pion-to-muon misidentification)
- much better $\tau^+\tau^-$ separation from $q\bar{q}$ background because of higher $q\bar{q}$ multiplicity at Z peak
- LHC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

Tau LFV decay upper limits, Belle II expected



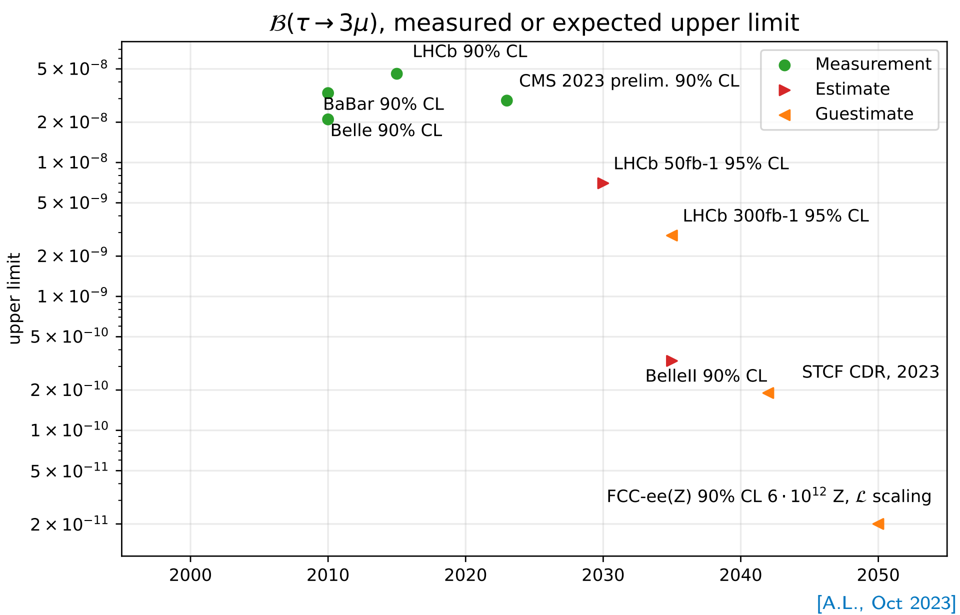
[Snowmass 2021 White Paper: Charged lepton flavor violation in the tau sector]

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



[A.L., Oct 2024]

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



Experimental LFV searches with tau in final state

$B^0 \to \mu^\pm e^\mp$	1.0×10^{-9}	90%	LHCb
$B_s^0 \to \mu^\pm e^\mp$	5.4×10^{-9}	90%	LHCb
$B^0 \to K^{*0}\mu^+ e^-$	5.7×10^{-9}	90%	LHCb
$B^0 \to K^{*0}\mu^- e^+$	6.8×10^{-9}	90%	LHCb
$B_s^0 \to \phi\mu^\pm e^\mp$	1.6×10^{-8}	90%	LHCb
$B^+ \to K^+\mu^+ e^-$	6.4×10^{-9}	90%	LHCb
$B^+ \to K^+\mu^- e^+$	7.0×10^{-9}	90%	LHCb
$B^0 \to \tau^\pm \mu^\mp$	1.5×10^{-5}	90%	LHCb
$B_s^0 \to \tau^\pm \mu^\mp$	4.2×10^{-5}	90%	LHCb
$B^0 \to \tau^\pm e^\mp$	1.6×10^{-5}	90%	Belle
$B^0 \to K^{*0}\tau^+ \mu^-$	1.0×10^{-5}	90%	LHCb
$B^0 \to K^{*0}\tau^- \mu^+$	8.2×10^{-6}	90%	LHCb
$D^0 \to \mu^\pm e^\mp$	1.3×10^{-8}	90%	LHCb
$D^+ \to \pi^+\mu^+ e^-$	2.2×10^{-7}	90%	LHCb
$D^+ \to \pi^+\mu^- e^+$	2.1×10^{-7}	90%	LHCb
$D^+ \to K^+\mu^+ e^-$	1.0×10^{-7}	90%	LHCb
$D^+ \to K^+\mu^+ e^-$	7.5×10^{-8}	90%	LHCb

$K_L^0 \to \mu^\pm e^\mp$	4.7×10^{-12}	90%	BNL
$K_L^0 \to e^\pm e^\pm \mu^\mp \mu^\mp$	4.12×10^{-11}	90%	KTeV
$K_L^0 \to \pi^0 \mu^\pm e^\mp$	7.56×10^{-11}	90%	KTeV
$K_L^0 \to \pi^0\pi^0 \mu^\pm e^\mp$	1.64×10^{-10}	90%	KTeV
$K^+ \to \mu^- \nu e^+ e^+$	8.1×10^{-11}	90%	NA62
$Z \to e^\pm \mu^\mp$	7.5×10^{-7}	95%	ATLAS
$Z \to e^\pm \tau^\mp$	5.0×10^{-6}	95%	ATLAS
$Z \to \mu^\pm \tau^\mp$	6.5×10^{-6}	95%	ATLAS
$H \to e^\pm \mu^\mp$	6.2×10^{-5}	95%	ATLAS
$H \to e^\pm \tau^\mp$	2.0×10^{-3}	95%	ATLAS
$H \to \mu^\pm \tau^\mp$	1.5×10^{-3}	95%	CMS

Lepton flavour universality

Experimental tests of lepton flavour universality

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

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

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

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

Lepton universality tests

today status [HFLAV 2023 report, preliminary]

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

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

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

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

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

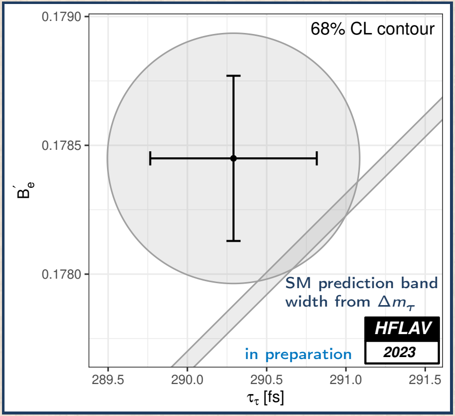
$$G_\mathcal{L} = \frac{g_\mathcal{L}^2}{4\sqrt{2}M_W^2}\;; \qquad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x\;; \qquad f_{\mathcal{L}\ell} = f\left(m_\ell^2/m_\mathcal{L}^2\right)$$

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

all statistical correlations included

- less precise tests possible with hadronic tau decays
- tau BF, mass, lifetime from HFLAV tau averates in preparation

Canonical tau lepton universality test plot



[HFLAV 2023 prelim.]

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

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

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 in preparation

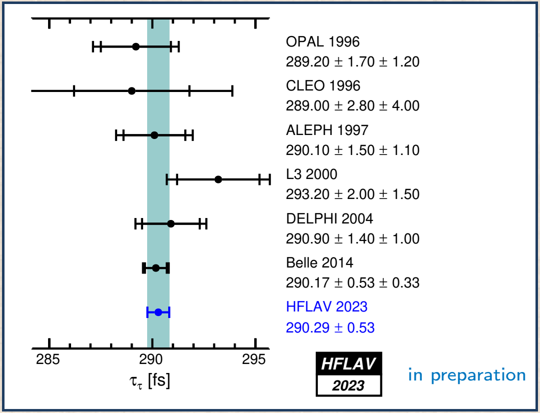
$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 0.996 \pm 0.004 , \qquad \left(\frac{g_\tau}{g_\mu}\right)_K = 0.986 \pm 0.008 .$$

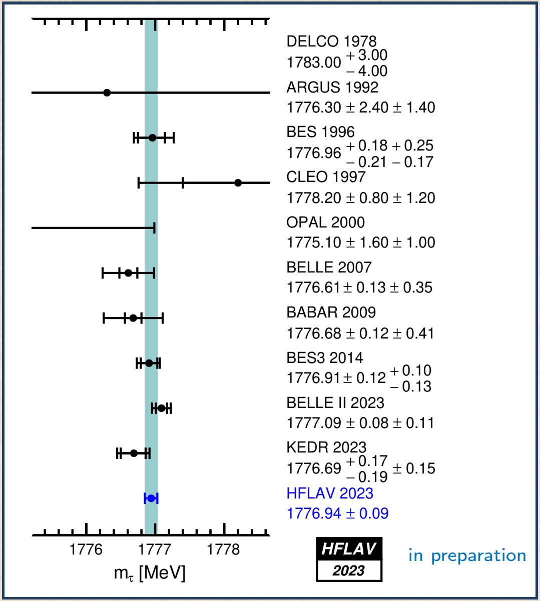
- $\mathcal{B}(\pi \to \mu\bar{\nu}_\mu)$, $\mathcal{B}(K \to \mu\bar{\nu}_\mu)$ PDG 2023

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

- 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

$\mathcal{B}_3 = \mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)$

0.17360 ± 0.00037	average
$0.17319 \pm 0.00070 \pm 0.00032$	ALEPH
$0.17325 \pm 0.00095 \pm 0.00077$	DELPHI
$0.17342 \pm 0.00110 \pm 0.00067$	L3
$0.17340 \pm 0.00090 \pm 0.00060$	OPAL

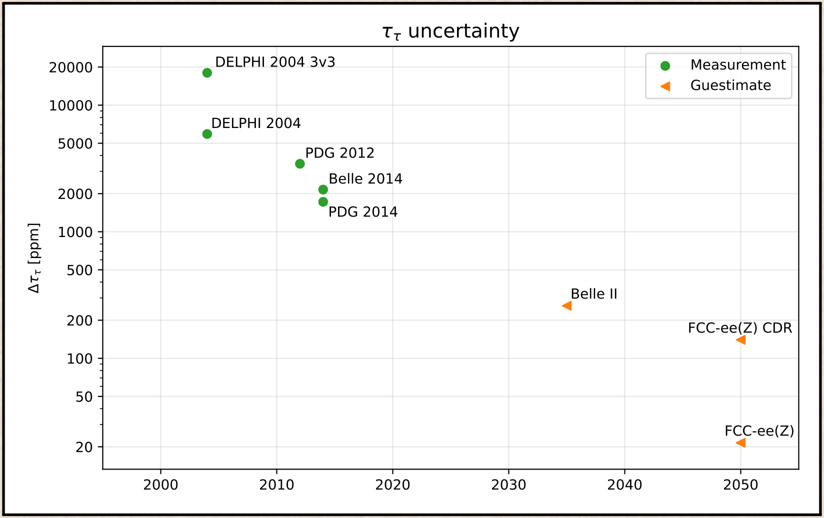
$\mathcal{B}_5 = \mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)$

0.1784 ± 0.0004	average
$0.1784 \pm 0.0007 \pm 0.0004$	ALEPH
$0.1776 \pm 0.0006 \pm 0.0017$	CLEO
$0.1788 \pm 0.0011 \pm 0.0011$	DELPHI
$0.1781 \pm 0.0010 \pm 0.0008$	L3
$0.1781 \pm 0.0009 \pm 0.0006$	OPAL

$$\mathcal{B}_{3/5} = \frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$$

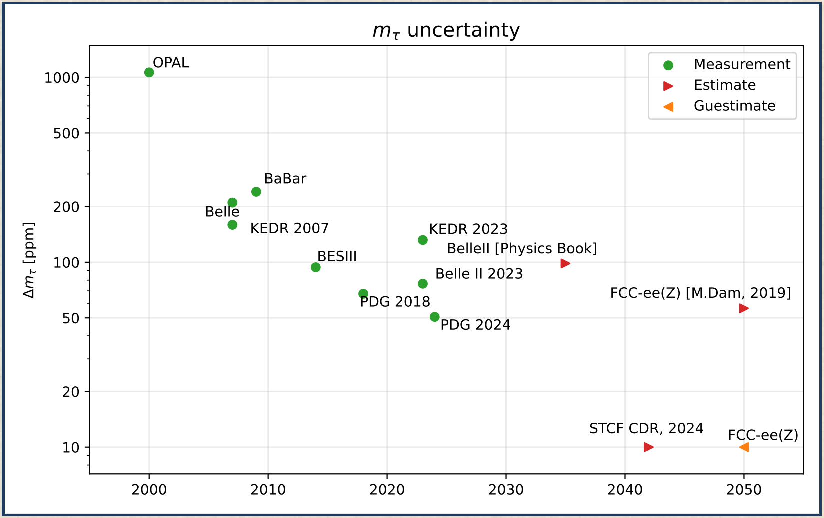
0.9730 ± 0.0022	average
$0.9970 \pm 0.0350 \pm 0.0400$	ARGUS
$0.9796 \pm 0.0016 \pm 0.0036$	*BaBar*
$0.9675 \pm 0.0007 \pm 0.0036$	Belle II
$0.9777 \pm 0.0063 \pm 0.0087$	CLEO

Tau Lifetime measurement prospects



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

Tau mass measurement prospects

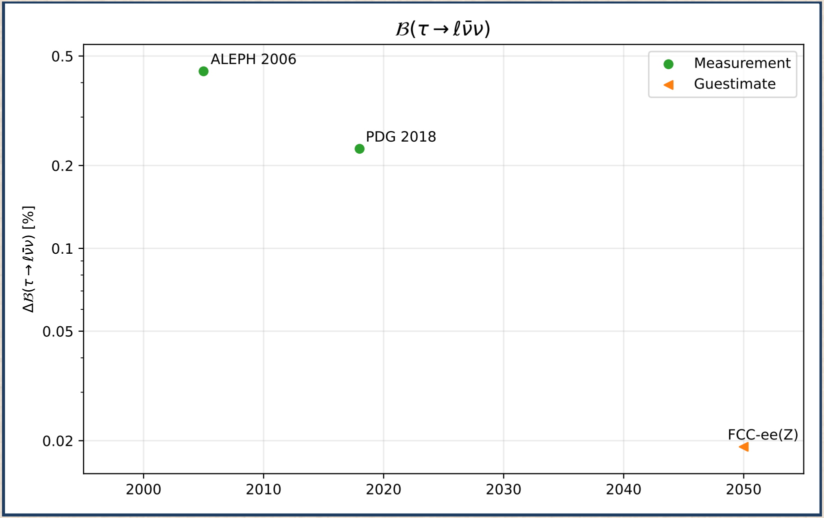


FCC-ee(Z) with $6{\cdot}10^{12}$ Z

Tau leptonic branching fractions measurement prospects

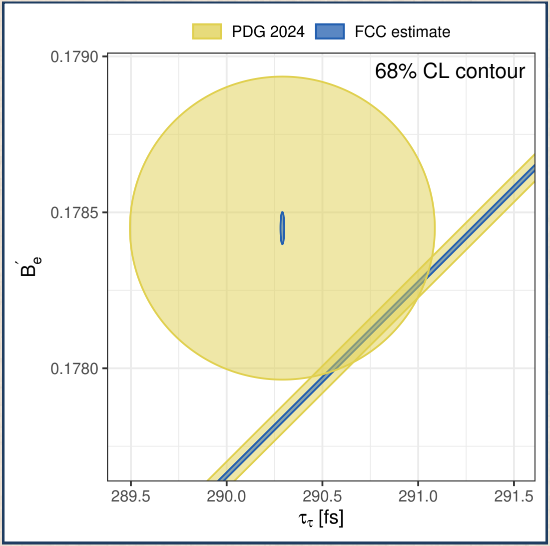
- ALEPH 2006 measurement precision: $4400\,\text{ppm} = [4000(\text{stat.}) \oplus 1900(\text{syst.})]\,\text{ppm}$
  (average of the two similar electron and muon decays branching fractions)
  - complex simultaneous measurement of 12 tau branching fractions
  - many systematic uncertainties, no reliable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

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 $\sim 1{\cdot}10^{-18}$