Lepton-flavour violation in hadronic tau decays and ℓ–τ conversion in nuclei

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Motivation

Neutrinos (neutral leptons) oscillate: $\nu_\ell \leftrightarrow \nu_{\ell'}$

- no known reason why lepton number in charged-lepton sector should be conserved

Minimal extensions of the SM predict negligible flavour violation in the charged-lepton sector (CLFV)

- new-physics scenarios allow for enhanced CLFV
  $\hookrightarrow$ extract information from experiment in a systematic way

Processes involving τ lepton

- most of up-to-date CLFV research involves only e and μ
- relevant experimental hints towards non-trivial lepton dynamics
  $\hookrightarrow$ violation of universality related to the third family
- rich phenomenology: hadronic tau decays

Our goal

Current experimental knowledge on τ-involved processes

- Best existing limits on CLFV hadronic τ decays
  - Belle Collaboration $\to$ HFLAV Collaboration (*Amhis et al.*, arXiv:1909.12524)
- Experimental prospects
  - Belle II (*Kou et al.*, PTEP 2019 (2019), arXiv:1808.10567)
    $\hookrightarrow$ improve on limits for hadronic τ decays by at least one order of magnitude
  - NA64 at CERN (*Gninenko et al.*, PRD 98 (2018))
    $\hookrightarrow$ expected sensitivity $R_{\ell\tau} = \dfrac{\sigma(\ell N \to \tau X)}{\sigma(\ell N \to \ell X)} \sim 10^{-12}\text{–}10^{-13}\,, \quad \ell = e, \mu$

Use SMEFT up to dim-6 operators to analyze τ-involved processes

- hadronic τ decays ($\ell \neq \nu_\tau$)
  - $\tau \to \ell P$: $\quad P = \pi^0, K^0, \eta, \eta'$
  - $\tau \to \ell P_1 P_2$: $\quad P_1 P_2 = \pi^+\pi^-, K^0\bar{K}^0, K^+K^-, \pi^+K^-, K^+\pi^-$
  - $\tau \to \ell V$: $\quad V = \rho^0(770), \omega(782), \phi(1020), K^{*0}(892), \bar{K}^{*0}(892)$
- ℓ–τ conversion in nuclei
  - $\ell N(A,Z) \to \tau X$: $\quad N(A,Z) = \mathrm{Fe}(56,26), \mathrm{Pb}(208,82)$
  - energy of the incident beam of leptons at NA64: $E_e = 100\,\mathrm{GeV}$ and $E_\mu = 150\,\mathrm{GeV}$

Global numerical analysis of channels above based on experimental limits from Belle, Belle II and NA64

SMEFT

Effects of new physics (emerging at scale Λ) on low-energy dynamics can be parametrized by

$$\mathcal{L}_{\mathsf{SMEFT}} = \mathcal{L}_{\mathsf{SM}} + \sum_{D>4} \frac{1}{\Lambda^{D-4}} \sum_i C_i^{(D)} \mathcal{O}_i^{(D)}, \qquad [\mathcal{O}_i^{(D)}] = [E^D]$$

SMEFT operator basis from *Grzadkowski et al.*, JHEP 10 (2010)

CLFV operators relevant for our analysis:

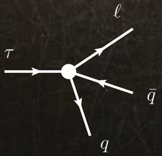
$\Lambda^2 \times$ Coupling	Operator	$\Lambda^2 \times$ Coupling	Operator
$C_{LQ}^{(1)}$	$(\bar{L}_p\gamma_\mu L_r)\,(\bar{Q}_s\gamma^\mu Q_t)$	$C_{e\varphi}$	$(\varphi^\dagger\varphi)\,(\bar{L}_p e_r \varphi)$
$C_{LQ}^{(3)}$	$(\bar{L}_p\gamma_\mu \sigma^I L_r)\,(\bar{Q}_s\gamma^\mu \sigma^I Q_t)$	$C_{\varphi e}$	$\left(\varphi^\dagger i\overset{\leftrightarrow}{D}_\mu \varphi\right)(e_p\gamma^\mu e_r)$
C_{eu}	$(\bar{e}_p\gamma_\mu e_r)\,(\bar{u}_s\gamma^\mu u_t)$	$C_{\varphi L}^{(1)}$	$\left(\varphi^\dagger i\overset{\leftrightarrow}{D}_\mu \varphi\right)(\bar{L}_p\gamma^\mu L_r)$
C_{ed}	$(\bar{e}_p\gamma_\mu e_r)\,(\bar{d}_s\gamma^\mu d_t)$	$C_{\varphi L}^{(3)}$	$\left(\varphi^\dagger i\overset{\leftrightarrow}{D}_{I\mu} \varphi\right)(\bar{L}_p\sigma_I\gamma^\mu L_r)$
C_{Lu}	$(\bar{L}_p\gamma_\mu L_r)\,(\bar{u}_s\gamma^\mu u_t)$	C_{eW}	$(\bar{L}_p\sigma^{\mu\nu} e_r)\,\sigma_I\varphi W_{\mu\nu}^I$
C_{Ld}	$(\bar{L}_p\gamma_\mu L_r)\,(\bar{d}_s\gamma^\mu d_t)$	C_{eB}	$(\bar{L}_p\sigma^{\mu\nu} e_r)\,\varphi B_{\mu\nu}$
C_{Qe}	$(\bar{Q}_p\gamma_\mu Q_r)\,(\bar{e}_s\gamma^\mu e_t)$		
C_{LedQ}	$\left(\bar{L}_p^j e_r\right)\left(\bar{d}_s Q_t^j\right)$		
$C_{LeQu}^{(1)}$	$\left(\bar{L}_p^j e_r\right)\varepsilon_{jk}\,(\bar{Q}_s^k u_t)$		
$C_{LeQu}^{(3)}$	$\left(\bar{L}_p^j \sigma_{\mu\nu} e_r\right)\varepsilon_{jk}\,(\bar{Q}_s^k \sigma^{\mu\nu} u_t)$		

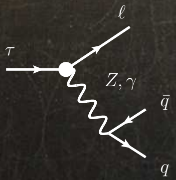
Hadronic τ decays

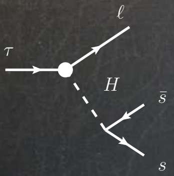
Contributions to the perturbative amplitude

Contributions of the SMEFT Lagrangian to $\tau \to \ell\,\bar{q}q$, for $\ell = e, \mu$

- We consider $m_u = m_d = 0$, but $m_s \neq 0$

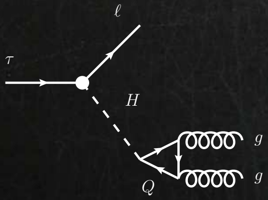






Dominant scalar contribution to $\tau \to \ell \bar{P} P$, for $\ell = e, \mu$ and $P = \pi, K$

- *Celis, Cirigliano and Passemar*, PRD 89 (2014)



Due to $m_\tau > 1\,\text{GeV} \to$ beyond χPT

- Resonance chiral theory (RχT) framework (*Ecker et al.*, NPB 321 (1989))
  - includes not only light pseudoscalar mesons, but also the lightest U(3) nonets of resonances

We add external sources (and associated fields $v^\mu, a^\mu, s, p, t^{\mu\nu}$) to the massless QCD Lagrangian $\mathcal{L}^0_{\text{QCD}}$

$$\mathcal{L}^{\text{ext}}_{\text{QCD}} = \mathcal{L}^0_{\text{QCD}} + \bar{\psi}\gamma_\mu\left(v^\mu + a^\mu\gamma_5\right)\psi - \bar{\psi}\left(s - ip\gamma_5\right)\psi + \bar{\psi}\sigma_{\mu\nu}\bar{t}^{\mu\nu}\psi$$

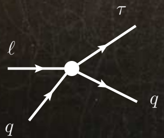
The hadronized quark bilinears are identified by taking derivatives of the RχT Lagrangian with respect to the external field. Symbolically,

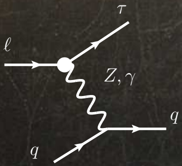
$$\bar{q}\,\gamma_{\{\mu\nu\}}\lambda^i\,q \Longleftrightarrow \left.\frac{\partial\mathcal{L}_{\text{R}\chi\text{T}}}{\partial x^i_{\{\mu\nu\}}}\right|_{j=0}$$

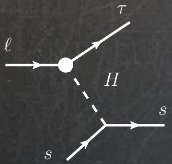
ℓ–τ conversion in nuclei

Perturbative part of the amplitude

1) Contributions of the SMEFT Lagrangian to $\ell q \to \tau q^{(\prime)}$, for $\ell = e, \mu$ and $q = u, d, s$
   - We consider $m_u = m_d = 0$, but $m_s \neq 0$

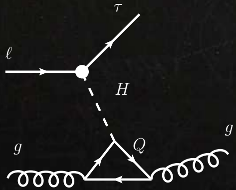


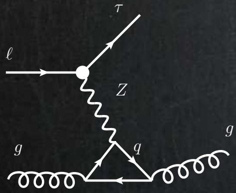




2) Accordingly, for $\ell \bar{q} \to \tau \bar{q}^{(\prime)}$

3) Higgs (dominant due to *Takeuchi et al.*, PLB 772 (2017)) and Z contribution to $\ell g \to \tau g$, for $\ell = e, \mu$
   - $Q = c, b, t$; $q = u, d, c, s, t, b$





Flavour conversion of charged leptons in the presence of nuclei

- μ–e
  - muon captured and muonic atom subsequently decays
  - strongest limit set by Sindrum II Collaboration (*Bertl et al.*, EPJ C 47 (2006))

$$B_{\mu e}^{\text{Au}} = \frac{\Gamma(\mu^- \text{Au} \to e^- \text{Au})}{\Gamma_{\text{capture}}(\mu^- \text{Au})} < 7 \times 10^{-13}\,, \quad 90\%\,\text{CL}$$

- μ–τ
  - fixed-target nucleus hit by incoming lepton beam (given flavour ℓ)
  - high enough energy $\to$ leptons penetrate the nucleus hadronic structure and interact with partons

We are interested in inclusive processes $\ell N(A,Z) \to \tau X$ (no information about X)

Interacting partons bound in nucleus $\to$ low-energy non-perturbative effects present

- factorization theorem
  - separate the perturbative and non-perturbative (encoded in PDFs) parts
  - once the perturbative calculation is performed $\to$ convolution with PDFs
    $\hookrightarrow$ total cross-section

ℓ–τ conversion in nuclei
Non-perturbative part: nuclear PDFs

Total cross section via convolution of perturbative cross section $\hat{\sigma}$ and PDFs f

$$\sigma_{\ell-\tau} = \hat{\sigma}(\xi, Q^2) \otimes f(\xi, Q^2)$$

- ξ fraction of nucleus momentum carried by the parton
- $Q^2 = -q^2$ transferred momentum (characteristic scale of the process)
  - PDFs determined at $Q_0^2 \overset{\text{DGLAP}}{\rightarrow}$ any scale Q^2

We deal with heavy nuclei instead of free nucleons

- nuclear binding effects alter significantly the non-perturbative behaviour at different ξ regimes
  - *European Muon Collaboration (Aubert et al.)*, PLB 123 (1983)
  - *Rojo*, arXiv:1910.03408

We use nCTEQ15-np fit of the nPDFs (*Kovarik et al.*, PRD 93 (2016))

- via Mathematica package ManeParse (*Clark et al.*, Comput. Phys. Commun. (2017))

LO QCD formalism (twist-2 factorization)

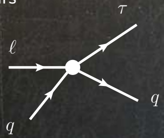
- our SMEFT perturbative cross sections calculated at tree level
- nCTEQ15 nPDFs computed at NLO
- works well for light quarks (for massless partons), larger uncertainties for contact-interaction contrbs.

$$\sigma(\ell\mathcal{N}(P) \to \tau X) = \sum_{z=q,\bar{q},g} \sum_{i,j} \int_{\xi_{\text{min}}}^{1} \int_{Q_-^2(\xi)}^{Q_+^2(\xi)} \mathrm{d}\xi\, \mathrm{d}Q^2 \frac{\mathrm{d}\hat{\sigma}(\ell z_i(\xi P) \to \tau z_j)}{\mathrm{d}\xi\, \mathrm{d}Q^2} f_{z_i}(\xi, Q^2)$$

Flavour-changing neutral currents

We allow for quark-flavour change

- we assume minimal flavour violation in the quark sector (only CKM)
  $\hookrightarrow$ we consider the same Wilson coefficients for all quark flavours
- we should consider quark currents like $\bar{c}u, \bar{b}s, \ldots$
  $\hookrightarrow$ only through local vertices



Consequently

- increase of the cross section $\rightarrow$ stronger constraints on WCs
- wider variety of final states for τ decays $\rightarrow$ more observables

BUT

- FCNC forbidden at LO in SM by GIM

We study both scenarios: CLFV ($\pm$ FCNC)
$\hookrightarrow$ same scale Λ for all new physics assumed

Operators $Q_{\varphi L}^{(1)}$ and $Q_{\varphi L}^{(3)}$ contribute the same way to CLFV τ processes

- we are sensitive only to $C_{\varphi L}^{(1)\prime} \equiv C_{\varphi L}^{(1)} + C_{\varphi L}^{(3)}$
- no-FCNC case $\rightarrow$ we cannot distinguish among $C_{\varphi L}^{(1)\prime}$ and $C_{LQ}^{(3)}$
  $\hookrightarrow C_{LQ}^{(3)\prime} \equiv C_{LQ}^{(3)} + C_{\varphi L}^{(1)} + C_{\varphi L}^{(3)}$

Similarly, we define C_γ and C_Z via the following a rotation: $\begin{pmatrix} C_\gamma \\ C_Z \end{pmatrix} = \begin{pmatrix} c_\mathrm{W} & -s_\mathrm{W} \\ s_\mathrm{W} & c_\mathrm{W} \end{pmatrix} \begin{pmatrix} C_{eB} \\ C_{eW} \end{pmatrix}$

Scale-independent C'_{LedQ} and $C_{LeQu}^{(1)\prime}$: $C_{LedQ} = \frac{m_i}{m_\tau} C'_{LedQ}\,, \quad C_{LeQu}^{(1)} = \frac{m_i}{m_\tau} C_{LeQu}^{(1)\prime}$

QCD running: $C_{LeQu}^{(3)}(m_\tau) = \left[\frac{\alpha_\mathrm{s}^4(m_\tau)}{\alpha_\mathrm{s}^4(m_b)}\right]^{-\frac{12}{75}} \left[\frac{\alpha_\mathrm{s}^5(m_b)}{\alpha_\mathrm{s}^5(\mu_{\ell-\tau})}\right]^{-\frac{12}{69}} C_{LeQu}^{(3)}(\mu_{\ell-\tau})$

Final set of WCs:

$$\{C_{LQ}^{(1)}, C_{LQ}^{(3)}, C_{eu}, C_{ed}, C_{Lu}, C_{Ld}, C_{Qe}, C'_{LedQ}, C_{LeQu}^{(1)\prime}, C_{LeQu}^{(3)}(m_\tau), C_{\varphi L}^{(1)\prime}, C_{\varphi e}, C_\gamma, C_Z, C_{e\varphi}\}$$

Numerical set-up

Every observable calculated within SMEFT will depend on several WCs and the scale Λ_{CLFV}
$\hookrightarrow$ we fit the ratio $C/\Lambda^2_{\text{CLFV}}$

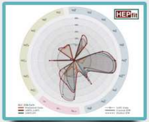
`HEPfit`

- open-source tool
- embedded with Bayesian statistical framework
- Markov Chain Monte Carlo analysis
- samples WC parameter space
  $\hookrightarrow$ gives allowed WC values at different confidence levels and their correlation
- *de Blas et al.*, arXiv:1910.14012

We use flat priors for WCs

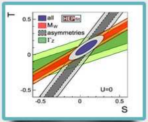
home developers physics documentation

HEPfit: a Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models



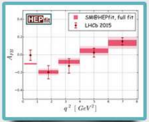
Higgs Physics

HEPfit can be used to study Higgs couplings and analyze data on signal strengths.



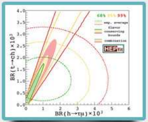
Precision Electroweak

Electroweak precision observables are included in HEPfit.



Flavour Physics

The Flavour Physics menu in HEPfit includes both quark and lepton flavour dynamics.

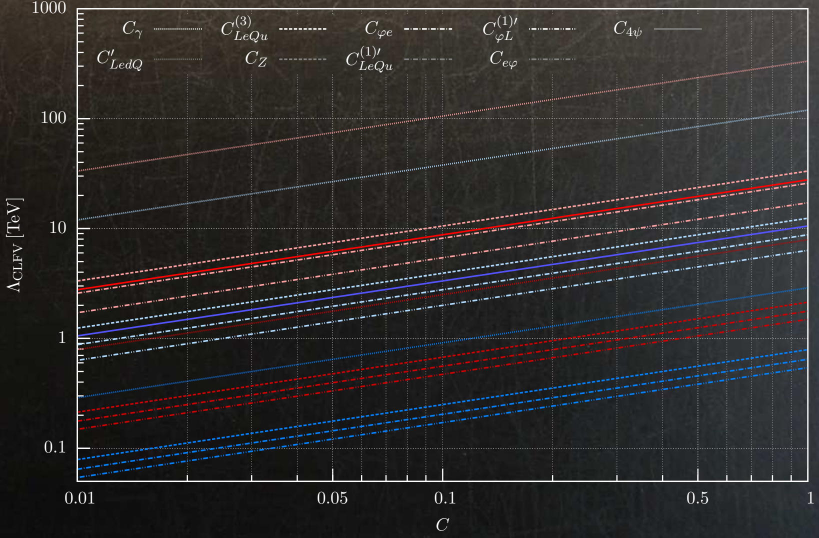


BSM Physics

Dynamics beyond the Standard Model can be studied by adding models in HEPfit.

Results: hadronic τ decays

Constraints on Λ_{CLFV} from present Belle and expected Belle II limits, 99.8% confidence level.



Results: hadronic τ decays

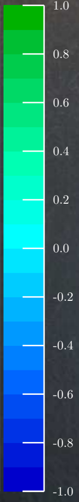
Constraints on Λ_{CLFV} [TeV], considering C ≈ 1, 99.8% CL

WC	Belle	Belle II	WC	Belle	Belle II
$C_{LQ}^{(1)}$	$\gtrsim 8.5$	$\gtrsim 26$	$C_{LeQu}^{(1)\prime}$	$\gtrsim 0.65$	$\gtrsim 1.8$
$C_{LQ}^{(3)}$	$\gtrsim 7.5$	$\gtrsim 21$	$C_{LeQu}^{(3)}$	$\gtrsim 12$	$\gtrsim 33$
C_{eu}	$\gtrsim 7.7$	$\gtrsim 22$	$C_{\varphi L}^{(1)\prime}$	$\gtrsim 6.3$	$\gtrsim 17$
C_{ed},C_{Ld}	$\gtrsim 10$	$\gtrsim 26$	$C_{\varphi e}$	$\gtrsim 8.8$	$\gtrsim 26$
C_{Lu}	$\gtrsim 6.5$	$\gtrsim 20$	C_{γ}	$\gtrsim 120$	$\gtrsim 330$
C_{Qe}	$\gtrsim 11$	$\gtrsim 28$	C_Z	$\gtrsim 0.79$	$\gtrsim 2.1$
C_{LedQ}'	$\gtrsim 2.9$	$\gtrsim 7.9$	$C_{e\varphi}$	$\gtrsim 0.54$	$\gtrsim 1.5$

Results: hadronic τ decays

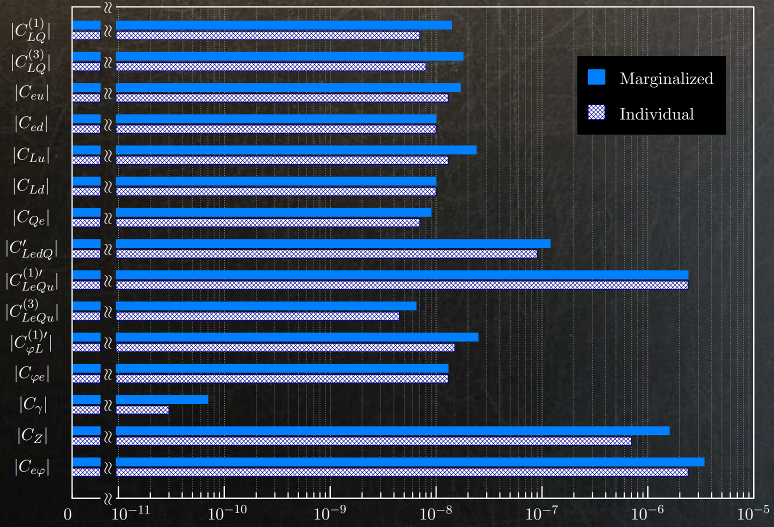
Correlation matrix, including FCNC

	$C_{LQ}^{(1)}$	$C_{LQ}^{(3)}$	C_{eu}	C_{ed}	C_{Lu}	C_{Ld}	C_{Qe}	C'_{LedQ}	$C_{LeQu}^{(1)\prime}$	$C_{LeQu}^{(3)}$	$C_{\varphi L}^{(1)\prime}$	$C_{\varphi e}$	C_{γ}	C_Z	$C_{e\varphi}$
$C_{LQ}^{(1)}$	+1	-0.74	+0.022	+0.056	-0.81	-0.42	+0.063	+0.035	-0.1	+0.074	-0.56	-0.078	+0.13	-0.19	+0.022
$C_{LQ}^{(3)}$	-0.74	+1	-0.001	-0.011	+0.76	+0.19	-0.08	+0.12	+0.13	-0.058	+0.84	+0.064	-0.1	+0.15	+0.1
C_{eu}	+0.022	-0.001	+1	+0.27	+0.099	-0.0054	-0.57	+0.071	-0.051	+0.11	+0.056	-0.18	+0.18	+0.019	+0.063
C_{ed}	+0.056	-0.011	+0.27	+1	-0.025	+0.015	-0.44	+0.18	+0.079	+0.035	-0.029	+0.15	+0.059	-0.12	+0.16
C_{Lu}	-0.81	+0.76	+0.099	-0.025	+1	+0.3	-0.043	+0.019	+0.14	+0.019	+0.57	+0.12	+0.041	+0.13	+0.028
C_{Ld}	-0.42	+0.19	-0.0054	+0.015	+0.3	+1	+0.035	-0.15	-0.047	+0.031	+0.24	-0.069	+0.034	-0.099	-0.12
C_{Qe}	+0.063	-0.08	-0.57	-0.44	-0.043	+0.035	+1	-0.17	+0.0048	+0.041	-0.091	+0.16	+0.079	-0.12	-0.14
C'_{LedQ}	+0.035	+0.12	+0.071	+0.18	+0.019	-0.15	-0.17	+1	+0.33	-0.02	+0.096	+0.034	-0.0005	-0.00059	+0.81
$C_{LeQu}^{(1)\prime}$	-0.1	+0.13	-0.051	+0.079	+0.14	-0.047	+0.0048	+0.33	+1	-0.026	+0.048	+0.12	+0.007	+0.0023	+0.33
$C_{LeQu}^{(3)}$	+0.074	-0.058	+0.11	+0.035	+0.019	+0.031	+0.041	-0.02	-0.026	+1	-0.05	-0.017	-0.58	+0.61	-0.02
$C_{\varphi L}^{(1)\prime}$	-0.56	+0.84	+0.056	-0.029	+0.57	+0.24	-0.091	+0.096	+0.048	-0.05	+1	+0.11	-0.067	+0.21	+0.079
$C_{\varphi e}$	-0.078	+0.064	-0.18	+0.15	+0.12	-0.069	+0.16	+0.034	+0.12	-0.017	+0.11	+1	+0.021	+0.18	+0.027
C_{γ}	+0.13	-0.1	+0.18	+0.059	+0.041	+0.034	+0.079	-0.0005	+0.007	-0.58	-0.067	+0.021	+1	-0.83	+0.01
C_Z	-0.19	+0.15	+0.019	-0.12	+0.13	-0.099	-0.12	-0.00059	+0.0023	+0.61	+0.21	+0.18	-0.83	+1	-0.0098
$C_{e\varphi}$	+0.022	+0.1	+0.063	+0.16	+0.028	-0.12	-0.14	+0.81	+0.33	-0.02	+0.079	+0.027	+0.01	-0.0098	+1



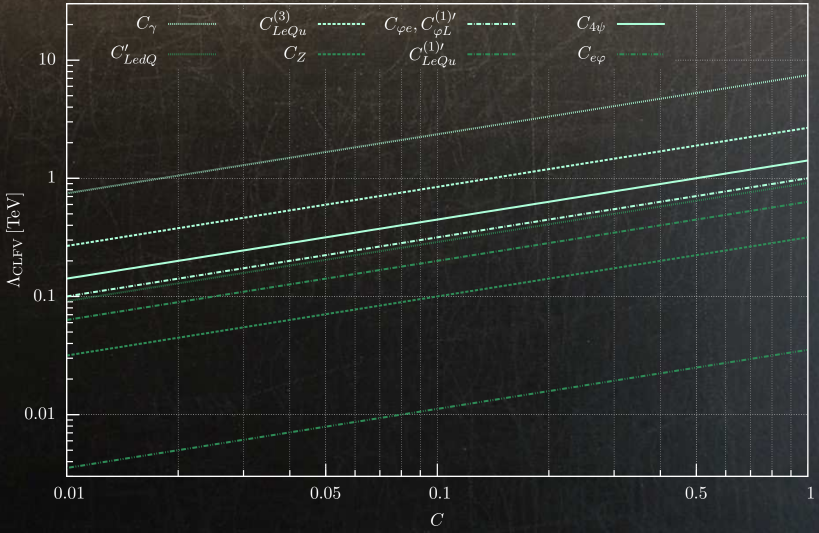
Results: hadronic τ decays

Constraints on $C/\Lambda^2_{\text{CLFV}}$ (GeV^{-2}) from the Marginalized/Individual analyses, present Belle limits, 99.8% CL



Results: μ–τ conversion in Fe(56,26)

Constraints on Λ_{CLFV} from expected NA64 sensitivity, 99.8% CL



Results: ℓ–τ conversion in Fe(56,26)

Constraints on Λ_{CLFV} [TeV] from expected NA64 sensitivity, considering C ≈ 1, 99.8% CL

WC	e–τ	μ–τ	WC	e–τ	μ–τ
$C_{LQ}^{(1)}$	$\gtrsim 0.13$	$\gtrsim 1.7$	C_{LedQ}	$\gtrsim 0.06$	$\gtrsim 0.9$
$C_{LQ}^{(3)}$	$\gtrsim 0.11$	$\gtrsim 1.5$	$C_{LeQu}^{(1)}$	$\gtrsim 0.05$	$\gtrsim 0.6$
C_{eu}	$\gtrsim 0.11$	$\gtrsim 1.4$	$C_{LeQu}^{(3)}$	$\gtrsim 0.2$	$\gtrsim 2.7$
C_{ed}	$\gtrsim 0.11$	$\gtrsim 1.4$	$C_{\varphi e}, C_{\varphi L}^{(1)}$	$\gtrsim 0.08$	$\gtrsim 1$
C_{Lu}	$\gtrsim 0.09$	$\gtrsim 1.1$	C_{γ}	$\gtrsim 0.6$	$\gtrsim 7.5$
C_{Ld}	$\gtrsim 0.09$	$\gtrsim 1.2$	C_{Z}	$\gtrsim 0.02$	$\gtrsim 0.3$
C_{Qe}	$\gtrsim 0.1$	$\gtrsim 1.4$	$C_{e\varphi}$	$\gtrsim 0.003$	$\gtrsim 0.04$

Summary

Model-independent numerical analysis of
SMEFT dim-6 operators related to CLFV processes involving
τ lepton

We studied 28 + 4 observables

- 14 different LFV τ decays into hadrons for each ℓ
- e–τ and μ–τ conversion in Fe(56,26) and Pb(208,82)
  - strongest constraints (due to normalization channel) imposed by μ–τ conversion in Fe(56,26)

Experimental inputs

- present Belle and expected Belle II limits on hadronic τ decays
- expected sensitivity of the NA64 experiment for ℓ–τ conversion in nuclei
  - cannot currently compete with Belle limits

  $\hookrightarrow$ an improvement of at least two orders of magnitude needed ($R_{\ell\tau} \sim 10^{-15}$)
  it would provide valuable complementary inputs

Statistical part performed in `HEPfit`

The paper will appear soon on arXiv: Stay tuned!

Thank you for listening!