Model-independent analysis of charged-lepton-flavour-violating τ processes

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(Collaboration with Tomáš Husek and Jorge Portolés)
Based on the published work [Husek et al., 2021]

Overview

1. Motivation

Neutrinos oscillate $\nu_\ell \leftrightarrow \nu_{\ell'}$

- Does this imply flavour violation in the charged-lepton sector (CLFV)?

The addition of a single right-handed neutrino predicts negligible CLFV effects

- New-physics scenarios allow for an enhancement of these phenomena

Processes involving τ lepton

- Most of up-to-date CLFV research involves only e and μ
  - already limits on the first and second family:
    $\mu N \to eN' \ \to \ R^{Au}_{\mu e} < 7 \times 10^{-13}$ (Sindrum II, 2006) [Bertl et al., 2006]
- Experimental hints to non-trivial lepton dynamics $\to$ violation of universality related to the third family
- Rich phenomenology: hadronic τ decays (Belle II)

2. Our project

Use of the SMEFT up to D-6 operators to analyse τ-involved processes

- Hadronic τ decays:

$$\begin{aligned} \tau &\rightarrow \ell P \\ \tau &\rightarrow \ell P P \qquad (\ell = e, \mu) \\ \tau &\rightarrow \ell V \end{aligned}$$

- $\ell - \tau$ conversion in nuclei:

$$\ell \; \mathcal{N}(A, Z) \quad \longrightarrow \quad \tau \; X$$

Current experimental knowledge on τ-involved processes

- Existing limits on hadronic τ decays
  - Belle and BaBar collaborations [Amhis et al., 2017]
- Experimental prospects
  - Belle II $\rightarrow$ improve limits for hadronic τ decays by at least one order of magnitude
  - NA64 experiment at CERN $\rightarrow$ expected sensitivity on $\ell - \tau$ conversion in nuclei
    $R_{\ell\tau} = \frac{\sigma(\ell + \mathcal{N} \rightarrow \tau + X)}{\sigma(\ell + \mathcal{N} \rightarrow \ell + X)} \sim 10^{-12} - 10^{-13}, \quad \ell = e, \mu$

Global numerical analysis of these processes based on the experimental limits from Belle, Belle II and tentatively NA64

SMEFT

$$\mathscr{L}_{SM} = \mathscr{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} \mathcal{Q}_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} \mathcal{Q}_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

[Grzadkowski et al., 2010]

CLFV operators relevant for our analysis [Husek et al., 2021]:

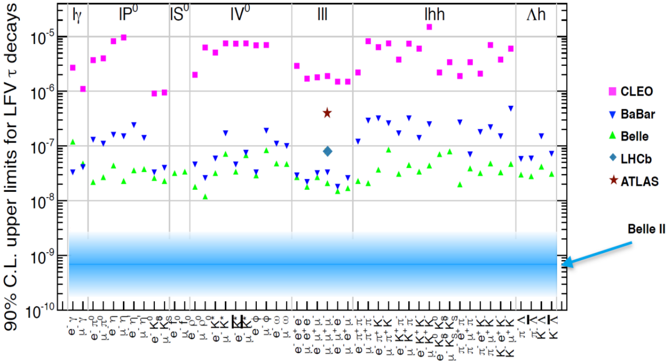
$\Lambda^2 \times$ Coupling	Operator	$\Lambda^2 \times$ Coupling	Operator
$C_{LQ}^{(1)}$	$(\bar{L}_p \gamma_\mu L_r)\,(\bar{Q}_s \gamma^\mu Q_t)$	$C_{e\varphi}$	$\left(\varphi^\dagger \varphi\right)\,(\bar{L}_p e_r \varphi)$
$C_{LQ}^{(3)}$	$\left(\bar{L}_p \gamma_\mu \sigma^I L_r\right)\,\left(\bar{Q}_s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

Hadronic τ decays

Due to $m_\tau \sim 2$ GeV, the hadronization of the quark currents in the D-6 operators are beyond Chiral perturbation theory (χPT) $\rightarrow$ Resonance chiral theory ($R\chi T$) framework is used
[Weinberg, 1979] [Ecker et al., 1989]

We consider three different flavour violating hadronic τ decays:

1. $\tau \rightarrow \ell P: \quad P = \pi^0, K^0, \bar{K}^0, \eta, \eta'$
2. $\tau \rightarrow \ell PP: \quad PP = \pi^+\pi^-, K^0\bar{K}^0, K^+K^-, \pi^+K^-, K^+\pi^-$
3. $\tau \rightarrow \ell V: \quad V = \rho^0, \phi, \omega, K^{*0}, \bar{K}^{*0}$



A. Rostomyan, TAU2018

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 and evolved perturbatively through DGLAP to 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 [Kovařík et al., 2016]

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

Our analysis

- Based on NA64 prospects [Gninenko et al., 2018]
- $\ell \mathcal{N}(A, Z) \to \tau X$: $\quad \mathcal{N}(A, Z) = Fe(56, 26), Pb(208, 82)$
- Energy of the incident beam of leptons: $E_e = 100$ GeV and $E_\mu = 150$ GeV

Numerical set-up

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

We assume minimal flavour violation in the quark sector (only CKM)

- Same Wilson coefficients for all quark flavours
- We consider quark currents like $\bar{c}u, \bar{b}s, \ldots$ through local vertices $\rightarrow$ assuming flavour-changing neutral currents (FCNC)
  - FCNC forbidden at LO in SM by GIM

We study both scenarios: CLFV ($\pm$ FCNC) $\rightarrow$ assuming $\Lambda_{\text{CLFV}} = \Lambda_{\text{FCNC}}$

Numerical analysis performed with HEPfit (http://hepfit.roma1.infn.it/), [De Blas et al., 2020]

QCD running

We work at the energy scale of the τ

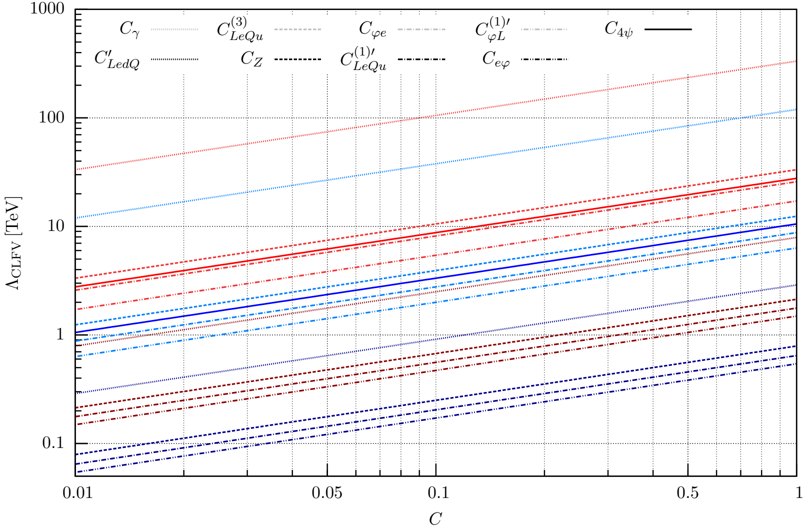
- Scale-independent C'_{LedQ} and $C^{(1)\prime}_{LeQu}$: $C_{LedQ} = \frac{m_i}{m_\tau} C'_{LedQ}$, $\qquad C^{(1)}_{LeQu} = \frac{m_i}{m_\tau} C^{(1)\prime}_{LeQu}$
- Running: $C^{(3)}_{LeQu}(m_\tau) = \left[\frac{\alpha_s^4(m_\tau)}{\alpha_s^4(m_b)}\right]^{-\frac{12}{75}} \left[\frac{\alpha_s^5(m_b)}{\alpha_s^5(\mu_{\ell-\tau})}\right]^{-\frac{12}{69}} C^{(3)}_{LeQu}(\mu_{\ell-\tau})$

Final set of WCs:

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

Results: hadronic τ decays

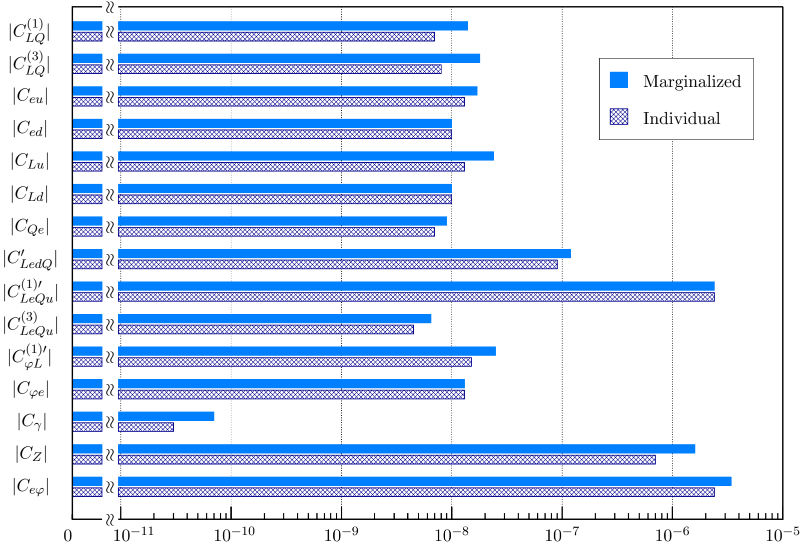
Constraints on Λ_{CLFV} from present Belle and expected Belle II bounds, 99.8% confidence level



Constraints on Λ_{CLFV} [TeV], considering $C \sim 1$, 99.8% confidence level

Bounds on Λ_{CLFV} [TeV]					
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}	$\gtrsim 0.79$	$\gtrsim 2.1$
$C_{LedQ}^{\prime}$	$\gtrsim 2.9$	$\gtrsim 7.9$	$C_{e\varphi}$	$\gtrsim 0.54$	$\gtrsim 1.5$

Constraints on C/Λ_{CLFV} (GeV^{-2}) from the Marginalized/Individual analysis, current Belle bounds, 99.8% confidence level



Results: $\ell - \tau$ conversion in Fe(56,26)

Constraints on Λ_{CLFV} [TeV] from expected NA64 sensitivity, considering $C \sim 1$, 99.8% confidence level

Bounds on Λ_{CLFV} [TeV]					
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}	$\gtrsim 0.1$	$\gtrsim 1.4$	$C_{e\varphi}$	$\gtrsim 0.003$	$\gtrsim 0.04$

Worse limits than τ decays but could remove correlations between WCs if improvement of at least two orders of magnitude ($R_{\tau\ell} \sim 10^{-15}$)

- A total of 5 scalar and 5 vectorial leptoquarks based on the representations of matter fields under the SM gauge group [Doršner et al., 2016]
- Keep only terms responsible for CLFV

LQ type	SM symmetries	Lagrangian
S_3	$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	$+Y^{\text{LL}}_{3,ij} \bar{Q}^{Ci,a}_{\text{L}} \epsilon^{ab} (\tau_k S^k_3)^{bc} L^{j,c}_{\text{L}} + \text{h.c.}$
R_2	$(\mathbf{3}, \mathbf{2}, 7/6)$	$-Y^{\text{RL}}_{2,ij} \bar{u}^i_{\text{R}} R^a_2 \epsilon^{ab} L^{j,b}_{\text{L}} + Y^{\text{LR}}_{2,ij} \bar{e}^i_{\text{R}} R^{a\dagger}_2 Q^{j,a}_{\text{L}} + \text{h.c.}$
$\tilde{R}_2$	$(\mathbf{3}, \mathbf{2}, 1/6)$	$-\tilde{Y}^{\text{RL}}_{2,ij} \bar{d}^i_{\text{R}} \tilde{R}^a_2 \epsilon^{ab} L^{j,b}_{\text{L}} + \text{h.c.}$
$\tilde{S}_1$	$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	$+\tilde{Y}^{\text{RR}}_{1,ij} \bar{d}^{C,i}_{\text{R}} \tilde{S}_1 e^j_{\text{R}} + \text{h.c.}$
S_1	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$+Y^{\text{LL}}_{1,ij} \bar{Q}^{Ci,a}_{\text{L}} S_1 \epsilon^{ab} L^{j,b}_{\text{L}} + Y^{\text{RR}}_{1,ij} \bar{u}^{Ci}_{\text{R}} S_1 e^j_{\text{R}} + \text{h.c.}$
U_3	$(\mathbf{3}, \mathbf{3}, 2/3)$	$+X^{\text{LL}}_{3,ij} \bar{Q}^{i,a}_{\text{L}} \gamma^\mu (\tau_k U^k_{3,\mu})^{ab} L^{j,b}_{\text{L}} + \text{h.c.}$
V_2	$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	$+X^{\text{RL}}_{2,ij} \bar{d}^{Ci}_{\text{R}} \gamma^\mu V^a_{2,\mu} \epsilon^{ab} L^{j,b}_{\text{L}} + X^{\text{LR}}_{2,ij} \bar{Q}^{Ci,a}_{\text{L}} \gamma^\mu V^b_{2,\mu} e^j_{\text{R}} + \text{h.c.}$
$\tilde{V}_2$	$(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$	$+\tilde{X}^{\text{RL}}_{2,ij} \bar{u}^{C,i}_{\text{R}} \gamma^\mu \tilde{V}^b_{2,\mu} \epsilon^{ab} L^{j,a}_{\text{L}} + \text{h.c.}$
$\tilde{U}_1$	$(\mathbf{3}, \mathbf{1}, 5/3)$	$+\tilde{X}^{\text{RR}}_{1,ij} \bar{u}^i_{\text{R}} \gamma^\mu \tilde{U}_{1,\mu} e^j_{\text{R}} + \text{h.c.}$
U_1	$(\mathbf{3}, \mathbf{1}, 2/3)$	$+X^{\text{LL}}_{1,ij} \bar{Q}^{i,a}_{\text{L}} \gamma^\mu U_{1,\mu} L^{j,a}_{\text{L}} + X^{\text{RR}}_{1,ij} \bar{d}^i_{\text{R}} \gamma^\mu U_{1,\mu} e^j_{\text{R}} + \text{h.c.}$

EFT of leptoquarks

1. Matching the SMEFT

We integrate out the leptoquarks at tree level to match the 4-fermion operators of the SMEFT

- Take the total derivative of the action resulting from the Lagrangian $\rightarrow$ EOM of the LQs
- m_S and m_V large $\rightarrow$ expansion in momenta $\rightarrow$ substituting rules for the LQ fields
- Insert these relations into the Lagrangian

$$\mathcal{L}_S^{\text{eff}} \supset \frac{Y_{d,ij}^{\chi_1\chi_2} Y_{d,mn}^{\chi_3\chi_4}}{m_S^2} (\bar{\psi}_{\chi_1}^i \psi_{\chi_2}^{\prime j})(\bar{\psi}_{\chi_4}^{\prime n} \psi_{\chi_3}^m) ,$$

$$\mathcal{L}_V^{\text{eff}} \supset \frac{X_{d,ij}^{\chi_1\chi_2} X_{d,mn}^{\chi_3\chi_4}}{m_V^2} (\bar{\psi}_{\chi_1}^i \gamma_\mu \psi_{\chi_2}^{\prime j})(\bar{\psi}_{\chi_4}^{\prime n} \gamma^\mu \psi_{\chi_3}^m) .$$

2. Flavour considerations

- Enhancement of flavour violation in the third family
- Minimal flavour violation in the quark sector $\rightarrow$ quark-flavour-blind Yukawas

$$Y_d^{\chi_1\chi_2} = \begin{pmatrix} y_d^{\chi_1\chi_2} & y_d^{\chi_1\chi_2} & y_{d\,\tau}^{\chi_1\chi_2} \\ y_d^{\chi_1\chi_2} & y_d^{\chi_1\chi_2} & y_{d\,\tau}^{\chi_1\chi_2} \\ y_d^{\chi_1\chi_2} & y_d^{\chi_1\chi_2} & y_{d\,\tau}^{\chi_1\chi_2} \end{pmatrix} , \qquad y_d^{\chi_1\chi_2} \neq y_{d\,\tau}^{\chi_1\chi_2}$$

Results: set-up

Bounds from CLFV τ processes translated to the leptoquark framework $\rightarrow$ bounds on $yy'/m^2_{S,V}$

Two independent scenarios $\rightarrow$ all scalar or vector leptquarks at the same time

- Same energy scale for all leptoquarks within the same scenario $\rightarrow$ equal masses

Previous assumption $\Lambda_{\text{CLFV}} = \Lambda_{\text{FCNC}}$ is better motivated

Bounds mainly from four-fermion operators of the SMEFT

- Gauge boson couplings to LQs leads to constraints on the same pairs of Yukawas
- Gauge bosons contribute through loop processes $\rightarrow$ lower sensitivity (except for the C_γ; see below)

Results: scalar leptoquarks

$\Lambda_{\rm CLFV} = m_S$

$$yy = f(C_i)$$

$$y_3^{\rm LL} y_{3\,\tau}^{\rm LL} = C_{LQ}^{(1)} + C_{LQ}^{(3)} \,,$$

$$y_2^{\rm RL} y_{2\,\tau}^{\rm RL} = -2 C_{Lu} \,, \qquad y_2^{\rm LR} y_{2\,\tau}^{\rm LR} = -2 C_{Qe} \,,$$

$$y_1^{\rm LL} y_{1\,\tau}^{\rm LL} = C_{LQ}^{(1)} - 3 C_{LQ}^{(3)} \,, \qquad y_1^{\rm RR} y_{1\,\tau}^{\rm RR} = 2 C_{eu} \,,$$

$$\tilde{y}_2^{\rm RL} \tilde{y}_{2\,\tau}^{\rm RL} = -2 C_{Ld} \,, \qquad \tilde{y}_1^{\rm RR} \tilde{y}_{1\,\tau}^{\rm RR} = 2 C_{ed} \,,$$

$$y_{2\,\tau}^{\rm RL} y_2^{\rm LR} = -C_{LeQu}^{(1)\,(\ell-\tau)} - 4 C_{LeQu}^{(3)\,(\ell-\tau)} \,, \qquad y_2^{\rm RL} y_{2\,\tau}^{\rm LR} = -C_{LeQu}^{(1)\,(\tau-h)} - 4 C_{LeQu}^{(3)\,(\tau-h)} \,,$$

$$y_{1\,\tau}^{\rm LL} y_1^{\rm RR} = C_{LeQu}^{(1)\,(\ell-\tau)} - 4 C_{LeQu}^{(3)\,(\ell-\tau)} \,, \qquad y_1^{\rm LL} y_{1\,\tau}^{\rm RR} = C_{LeQu}^{(1)\,(\tau-h)} - 4 C_{LeQu}^{(3)\,(\tau-h)}$$

- Pairs of Yukawas $y_{2\tau}^{RL} y_2^{LR}$ and $y_{1\tau}^{LL} y_1^{RR}$ unconstrained by τ decays $\to$ $\ell - \tau$ conversion limits considered
- 11 pairs of Yukawas and 11 effective bounds on the WCs

τ decays	Bounds on Λ_{CLFV} [TeV]		Bounds on Yukawas $[10^{-3}]$	
Yukawas	Belle	Belle II	Belle	Belle II
$\lvert y_3^{\text{LL}} y_{3\tau}^{\text{LL}} \rvert$	$\gtrsim 9.1$	$\gtrsim 23$	$\lesssim 12$	$\lesssim 1.9$
$\lvert y_2^{\text{RL}} y_{2\tau}^{\text{RL}} \rvert$	$\gtrsim 4.6$	$\gtrsim 14$	$\lesssim 47$	$\lesssim 5.0$
$\lvert y_2^{\text{LR}} y_{2\tau}^{\text{LR}} \rvert$	$\gtrsim 7.8$	$\gtrsim 20$	$\lesssim 17$	$\lesssim 2.6$
$\lvert y_2^{\text{RL}} y_{2\tau}^{\text{LR}} \rvert$	$\gtrsim 6.0$	$\gtrsim 16$	$\lesssim 28$	$\lesssim 3.7$
$\lvert \tilde{y}_2^{\text{RL}} \tilde{y}_{2\tau}^{\text{RL}} \rvert$, $\lvert \tilde{y}_1^{\text{RR}} \tilde{y}_{1\tau}^{\text{RR}} \rvert$	$\gtrsim 7.1$	$\gtrsim 18$	$\lesssim 20$	$\lesssim 3.0$
$\lvert y_1^{\text{LL}} y_{1\tau}^{\text{LL}} \rvert$	$\gtrsim 3.9$	$\gtrsim 11$	$\lesssim 64$	$\lesssim 7.7$
$\lvert y_1^{\text{RR}} y_{1\tau}^{\text{RR}} \rvert$	$\gtrsim 5.4$	$\gtrsim 16$	$\lesssim 34$	$\lesssim 4.1$
$\lvert y_1^{\text{LL}} y_{1\tau}^{\text{RR}} \rvert$	$\gtrsim 6.0$	$\gtrsim 16$	$\lesssim 28$	$\lesssim 3.7$

ℓ–τ conversion	Bounds on Λ_{CLFV} [TeV]		Bounds on Yukawas $[10^{0}]$	
Yukawas	e–τ	μ–τ	e–τ	μ–τ
$\lvert y_{2\tau}^{\text{RL}} y_2^{\text{LR}} \rvert$	$\gtrsim 0.054$	$\gtrsim 0.66$	$\lesssim 350$	$\lesssim 2.3$
$\lvert y_{1\tau}^{\text{LL}} y_1^{\text{RR}} \rvert$	$\gtrsim 0.063$	$\gtrsim 0.75$	$\lesssim 250$	$\lesssim 1.8$

To match the C_γ consider gauge couplings of the leptoquarks

- Vector leptoquarks
  - the uncertainty on their origin — UV completion — hinders to extract meaningful information $\rightarrow$ not considered [Gonderinger and Ramsey-Musolf, 2010]
- Scalar leptoquarks
  - coupled through the covariant derivative

Leading-order contribution within the LQ framework to C_γ $\rightarrow$ one-loop comuptation of $\ell_1 \rightarrow \ell_2\gamma$ process

- Integration by regions [Fuentes-Martín et al., 2016]
- Main contribution from two leptoquarks: $R_2^{5/3}$ and S_1

$$\frac{C_\gamma}{\Lambda^2_{\mathrm{CLFV}}} = \frac{e m_t V_{tb}}{32\sqrt{2}\pi^2 v m_S^2}(Q_{LQ} - 3Q_t) y_1 y_2 \longrightarrow \begin{cases} R_2^{5/3}: & Q_{LQ} = 5/3;\ y_1 y_2 = y_{2\tau}^{RL} y_2^{LR} \\ S_1: & Q_{LQ} = 1/3;\ y_1 y_2 = y_{1\tau}^{LL} y_1^{RR} \end{cases}$$

$(C_\gamma/\Lambda^2_{\mathrm{CLFV}})^{\tau-h}$	Bounds on Λ_{CLFV} [TeV]		Bounds on Yukawas $[10^{-2}]$	
Yukawas	Belle	Belle II	Belle	Belle II
$\lvert y^{\mathrm{RL}}_{2\,\tau} y^{\mathrm{LR}}_2 \rvert$	$\gtrsim 1.8$	$\gtrsim 5$	$\lesssim 0.44$	$\lesssim 0.057$
$\lvert y^{\mathrm{LL}}_{1\,\tau} y^{\mathrm{RR}}_1 \rvert$	$\gtrsim 4.7$	$\gtrsim 13$	$\lesssim 0.063$	$\lesssim 0.0081$

Conclusions

Model-independent numerical analysis of SMEFT D-6 operators related to CLFV processes the τ lepton

We studied 28+4 observables

- 14 different LFV τ decay channels into hadrons for each ℓ $\rightarrow$ we used current Belle and expected Belle II data (strongest bounds)
- $e - \tau$ and $\mu - \tau$ conversion in Fe(56,26) and Pb(208,82) $\rightarrow$ feasible at NA64
  - not competitive yet, could remove correlations between WCs if improvement of at least two orders of magnitude ($R_{\tau\ell} \sim 10^{-15}$)

Statistical part performed by HEPfit $\rightarrow$ we showed the importance of the Marginalized analyses over the single-parameter analyses

We translated the bounds on the SMEFT parameters into constraints on the most general leptoquark framework

- We integrated away the heavy leptoquarks and related their Yukawas to the WCs

Main constraints from four-fermion operators (tree-level contributions)

- Some pairs of Yukawas only bounded from $\ell - \tau$ conversion
- The main bound on C_γ from τ decays helps improving these low-bounded pair of Yukawas
  - not competitive against four-fermion bounds anyway

The article with the leptoquark analysis will appear soon on arXiv: Stay tuned!

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http://lhcpheno.ific.uv-csic.es/

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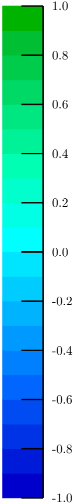
Correlation matrix: Belle

	$C_{LQ}^{(1)}$	$C_{LQ}^{(3)}$	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: vector leptoquarks

$\Lambda_{\text{CLFV}} = m_V$

- We start with 11 pairs of Yukawas but 9 effective bounds on the WCs

$$\frac{1}{2}\, C_{LedQ}^{(\ell-\tau)} = x_{1\,\tau}^{\text{LL}} x_{1}^{\text{RR}} - x_{2\,\tau}^{\text{RL}} x_{2}^{\text{LR}} \equiv x_{1,2}^{(\ell-\tau)}\,, \qquad \frac{1}{2}\, C_{LedQ}^{(\tau-h)} = x_{1}^{\text{LL}} x_{1\,\tau}^{\text{RR}} - x_{2}^{\text{RL}} x_{2\,\tau}^{\text{LR}} \equiv x_{1,2}^{(\tau-h)}$$

$$\Downarrow$$

$$x_{3}^{\text{LL}} x_{3\,\tau}^{\text{LL}} = \frac{1}{2}\left(C_{LQ}^{(3)} - C_{LQ}^{(1)}\right), \quad x_{2}^{\text{RL}} x_{2\,\tau}^{\text{RL}} = C_{Ld}\,, \quad x_{2}^{\text{LR}} x_{2\,\tau}^{\text{LR}} = C_{Qe}\,,$$

$$\tilde{x}_{2}^{\text{RL}} \tilde{x}_{2\,\tau}^{\text{RL}} = C_{Lu}\,, \quad x_{1}^{\text{LL}} x_{1\,\tau}^{\text{LL}} = -\frac{1}{2}\left(C_{LQ}^{(1)} + 3C_{LQ}^{(3)}\right), \quad x_{1}^{\text{RR}} x_{1\,\tau}^{\text{RR}} = -C_{ed}\,,$$

$$\tilde{x}_{1}^{\text{RR}} \tilde{x}_{1\,\tau}^{\text{RR}} = -C_{eu}\,, \quad x_{1,2}^{(\tau-h)} = \frac{1}{2}\, C_{LedQ}^{(\tau-h)}\,, \quad x_{1,2}^{(\ell-\tau)} = \frac{1}{2}\, C_{LedQ}^{(\ell-\tau)}\,.$$

- $x_{1,2}^{(\ell-\tau)}$ unconstrained by τ decays $\to$ $\ell-\tau$ conversion limits considered
- 9 pairs of Yukawas and 9 effective bounds on the WCs

τ decays	Bounds on Λ_{CLFV} [TeV]		Bounds on Yukawas $[10^{-3}]$	
Yukawas	Belle	Belle II	Belle	Belle II
$\lvert x_3^{LL} x_{3\,\tau}^{LL}\rvert$	$\gtrsim 8.2$	$\gtrsim 25$	$\lesssim 15$	$\lesssim 1.7$
$\lvert x_2^{RL} x_{2\,\tau}^{RL}\rvert$, $\lvert x_1^{RR} x_{1\,\tau}^{RR}\rvert$	$\gtrsim 10$	$\gtrsim 26$	$\lesssim 10$	$\lesssim 1.5$
$\lvert x_2^{LR} x_{2\,\tau}^{LR}\rvert$	$\gtrsim 11$	$\gtrsim 28$	$\lesssim 8.3$	$\lesssim 1.3$
$\lvert \tilde{x}_2^{RL} \tilde{x}_{2\,\tau}^{RL}\rvert$	$\gtrsim 6.5$	$\gtrsim 20$	$\lesssim 24$	$\lesssim 2.5$
$\lvert x_1^{LL} x_{1\,\tau}^{LL}\rvert$	$\gtrsim 6.7$	$\gtrsim 18$	$\lesssim 22$	$\lesssim 3.1$
$\lvert \tilde{x}_1^{RR} \tilde{x}_{1\,\tau}^{RR}\rvert$	$\gtrsim 7.7$	$\gtrsim 22$	$\lesssim 17$	$\lesssim 2.1$
$\lvert x_{1,2}^{(\tau-h)}\rvert$	$\gtrsim 18$	$\gtrsim 49$	$\lesssim 3.1$	$\lesssim 0.42$

ℓ–τ conversion	Bounds on Λ_{CLFV} [TeV]		Bounds on Yukawas $[10^{0}]$	
Yukawas	e–τ	μ–τ	e–τ	μ–τ
$\lvert x_{1,2}^{(\ell-\tau)}\rvert$	$\gtrsim 0.055$	$\gtrsim 0.83$	$\lesssim 330$	$\lesssim 1.5$

Gauge couplings of vector leptoquarks

Vector leptoquarks interaction with the photon depend on their nature $\rightarrow$ gauge bosons or not of a higher energy theory

- there can exist an anomalous magnetic moment coupling

$$\mathcal{L}_{V,\gamma} = -ieQ_V \left(\left[\mathcal{V}^{\dagger}_{\mu\nu} V^{\nu} - \mathcal{V}_{\mu\nu} V^{\nu\dagger} \right] A^{\mu} - (1-\kappa) V^{\dagger}_{\mu} V_{\nu} F^{\mu\nu} \right)$$

- gauge boson $\rightarrow \kappa = 0$
    - three-gauge-boson vertex

If gauge boson, propagator:

$$\frac{-ig^{\mu\nu}}{k^2 - m_V^2 + i\epsilon},$$

otherwise

$$\frac{-i}{k^2 - m_V^2 + i\epsilon} \left(g^{\mu\nu} - \frac{k^{\mu} k^{\nu}}{m_V^2} \right)$$

Second term introduces extra divergences to the loop computations of $\ell_1 \rightarrow \ell_2 \gamma$

- they do not cancel as for scalar leptoquarks

If gauge boson, possible contributions to the loop from other defrees of freedom in the UV completion