Constraints on leptoquarks from charged-lepton-flavour-violating τ processes

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Based on the published work [Husek et al., 2022]

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Overview

Preceding project

Use of the SMEFT up to D-6 operators to analyse τ-involved processes [Husek et al., 2021]

- Hadronic τ decays:

$$\begin{aligned} \tau &\rightarrow \ell P: && P = \pi^0, K^0, \bar{K}^0, \eta, \eta' \\ \tau &\rightarrow \ell PP: && PP = \pi^+\pi^-, K^0\bar{K}^0, K^+K^-, \pi^+K^-, K^+\pi^- \qquad (\ell = e, \mu) \\ \tau &\rightarrow \ell V: && V = \rho^0, \phi, \omega, K^{*0}, \bar{K}^{*0} \end{aligned}$$

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

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

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 — implemented with HEPfit [De Blas et al., 2020] — of these processes based on the experimental limits from Belle, Belle II and tentatively NA64

$$\mathscr{L}_{SM} = \mathscr{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)}\mathcal{O}_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)}\mathcal{O}_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$ [Grzadkowski et al., 2010]

CLFV operators ($\Lambda = \Lambda_{\text{CLFV}}$) relevant for our analysis [Husek et al., 2021]:

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

Two scenarios

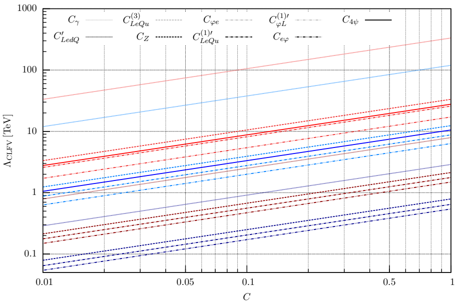
1. Quark-flavour diagonal WCs: no FCNC in the quark sector
2. Equal entries for the full 3×3 quark-flavour WC matrix: FCNC in the quark sector (quark currents like $\bar{c}u$, $\bar{b}s\ldots$) is allowed. $\Lambda_{\text{CLFV}} = \Lambda_{\text{FCNC}}$

Most stringent bound found for

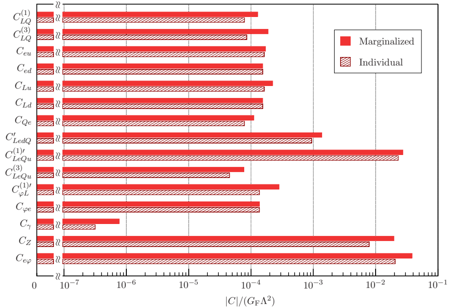
$$\mathcal{O}_\gamma \equiv c_W\mathcal{O}_{eB} - s_W\mathcal{O}_{eW} \xrightarrow{C_\gamma\sim1} \Lambda_{\text{CLFV}}[\text{TeV}] \gtrsim \begin{cases} 120 & \text{Belle} \\ 330 & \text{Belle II} \end{cases}$$

– Belle and Belle II limits on τ decays dominate the analysis

– NA64 expected sensitivity on ℓ-τ conversion in nuclei is not competitive, but could remove correlations between WCs if improvement of at least two orders of magnitude ($R_{\tau\ell} \sim 10^{-15}$)



Constraints on $\Lambda_{\rm CLFV}$ from present Belle and expected Belle II bounds



Constraints on $|C|/(G_F\Lambda^2_{\rm CLFV})$ from expected Belle II bounds

Leptoquark Lagrangian

The most general framework: 5 scalar and 5 vectorial leptoquarks based on the representations of matter fields under the SM gauge group [Doršner et al., 2016] [Crivellin et al., 2021]

$$\mathcal{L}_{\text{UV}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{LQ-}\psi} + \mathcal{L}_{\text{S}} + \mathcal{L}_{\text{V}} + \mathcal{L}_{\text{LQ-}H}$$

Keep only terms responsible for CLFV: LQ-ψ, γ-mediated, Z-mediated and H-mediated

$\mathcal{L}_{\text{LQ-}\psi} \supset$

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	$(\mathbf{3}, \mathbf{1}, 2/3)$	$+X^{\text{LL}}_{1,ij}\bar{Q}^{i,a}_{\text{L}}\gamma^\mu U_{1,\mu}L^{j,a}_{\text{L}} + X^{\text{RR}}_{1,ij}\bar{d}^i_{\text{R}}\gamma^\mu U_{1,\mu}e^j_{\text{R}} + \text{h.c.}$

$\mathcal{L}_{\text{S}} \supset$

$$\mathcal{L}^\gamma_{\text{S}} = ie\sum_{\text{Scalar LQs}} Q_{\text{S}}\left[\left(\partial_\mu S^\dagger\right)S - S^\dagger\left(\partial_\mu S\right)\right]A^\mu$$

1. Matching $\mathcal{L}_{\text{LQ-}\psi}$ to 4ψ SMEFT operators

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 $\mathcal{L}_{\text{UV}} \rightarrow$ 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
- Equal entries quark-flavour WC matrix $\rightarrow$ 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: scalar leptoquarks

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

$$yy = f(C_i)$$

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

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

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

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

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

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

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

τ decays	Upper bounds on $\frac{\lvert yy'\rvert}{M_S^2}$ $[10^{-3}\ \mathrm{TeV}^{-2}]$		Lower bounds on M_S [TeV]	
Yukawa pair	Belle	Belle II	Belle	Belle II
$\lvert y_3^{LL} y_{3\,\tau}^{LL}\rvert$	12	1.9	9.1	23
$\lvert y_2^{RL} y_{2\,\tau}^{RL}\rvert$	47	5.0	4.6	14
$\lvert y_2^{LR} y_{2\,\tau}^{LR}\rvert$	17	2.6	7.8	20
$\lvert y_2^{RL} y_{2\,\tau}^{LR}\rvert$	28	3.7	6.0	16
$\lvert \tilde{y}_2^{RL} \tilde{y}_{2\,\tau}^{RL}\rvert$, $\lvert \tilde{y}_1^{RR} \tilde{y}_{1\,\tau}^{RR}\rvert$	20	3.0	7.1	18
$\lvert y_1^{LL} y_{1\,\tau}^{LL}\rvert$	64	7.7	3.9	11
$\lvert y_1^{RR} y_{1\,\tau}^{RR}\rvert$	34	4.1	5.4	16
$\lvert y_1^{LL} y_{1\,\tau}^{RR}\rvert$	28	3.7	6.0	16

ℓ–τ conversion	Upper bounds on $\frac{\lvert yy'\rvert}{M_S^2}$ $[10^{0}\ \mathrm{TeV}^{-2}]$		Lower bounds on M_S [TeV]	
Yukawa pair	e–τ	μ–τ	e–τ	μ–τ
$\lvert y_{2\,\tau}^{RL} y_2^{LR}\rvert$	350	2.3	0.054	0.66
$\lvert y_{1\,\tau}^{LL} y_1^{RR}\rvert$	250	1.8	0.063	0.75

Results: C_γ

To match the C_γ consider gauge couplings of the leptoquarks

- Vector leptoquarks
  - uncertainty on their origin $\to$ not considered [Gonderinger and Ramsey-Musolf, 2010]
- Scalar leptoquarks
  - coupled through the covariant derivative

Leading-order contribution to C_γ from LQs $\to$ one-loop computation of $\ell_1 \to \ell_2\gamma$ process

- Integration by regions [Beneke and Smirnov, 1998] [Smirnov, 2002] [Jantzen, 2011]
- Main contribution from two leptoquarks: $R_2^{5/3}$ and S_1

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

$C_\gamma/\Lambda^2_{\text{CLFV}}$	Upper bounds on $\frac{\lvert yy'\rvert}{M_S^2}$ $[10^{-3}\ \text{TeV}^{-2}]$		Lower bounds on M_S [TeV]	
Yukawa pair	Belle	Belle II	Belle	Belle II
$\lvert y_{2\tau}^{RL} y_2^{LR}\rvert$	150	19	3.1	8.6
$\lvert y_{1\tau}^{LL} y_1^{RR}\rvert$	21	2.7	8.2	23

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 $\ell \to$ 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) $\to$ feasible at NA64
  - not competitive yet, could remove correlations between WCs if improvement of at least two orders of magnitude ($R_{\tau\ell} \sim 10^{-15}$)

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

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

- Strongest bound on scalar LQs: $|y_{3}^{\mathrm{LL}} y_{3\,\tau}^{\mathrm{LL}}| \sim 1 \longrightarrow M_{\mathrm{S}} \gtrsim 23\mathrm{TeV}$ (Belle II)
- Slightly stronger bounds on vector LQs
- Some pairs of Yukawas only bounded from $\ell - \tau$ conversion

Main bound on C_γ (one-loop LQ contribution) from τ decays helps improving the low-bounded pair of Yukawas

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

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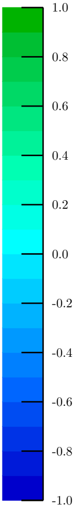
	$C_{LQ}^{(1)}$	$C_{LQ}^{(3)}$	C_{eu}	C_{ed}	C_{Lu}	C_{Ld}	C_{Qe}	C'_{LedQ}	$C_{LeQu}^{(1)\prime}$	$C_{LeQu}^{(3)}$	$C_{\varphi L}^{(1)\prime}$	$C_{\varphi e}$	C_{γ}	C_Z	$C_{e\varphi}$
$C_{LQ}^{(1)}$	+1	-0.74	+0.022	+0.056	-0.81	-0.42	+0.063	+0.035	-0.1	+0.074	-0.56	-0.078	+0.13	-0.19	+0.022
$C_{LQ}^{(3)}$	-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: set-up

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

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

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

Previous 2$^{\text{nd}}$ scenario 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)

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

- 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	Upper bounds on $\frac{\lvert xx'\rvert}{M_V^2}$ $[10^{-3}\ \text{TeV}^{-2}]$		Lower bounds on M_V [TeV]	
Yukawa pair	Belle	Belle II	Belle	Belle II
$\lvert x_3^{LL} x_{3\,\tau}^{LL}\rvert$	15	1.7	8.2	25
$\lvert x_2^{RL} x_{2\,\tau}^{RL}\rvert$, $\lvert x_1^{RR} x_{1\,\tau}^{RR}\rvert$	10	1.5	10	26
$\lvert x_2^{LR} x_{2\,\tau}^{LR}\rvert$	8.3	1.3	11	28
$\lvert \tilde{x}_2^{RL} \tilde{x}_{2\,\tau}^{RL}\rvert$	24	2.5	6.5	20
$\lvert x_1^{LL} x_{1\,\tau}^{LL}\rvert$	22	3.1	6.7	18
$\lvert \tilde{x}_1^{RR} \tilde{x}_{1\,\tau}^{RR}\rvert$	17	2.1	7.7	22
$\lvert x_{1,2}^{\tau h}\rvert$	3.1	0.42	18	49

ℓ–τ conversion	Upper bounds on $\frac{\lvert xx'\rvert}{M_V^2}$ $[10^{0}\ \text{TeV}^{-2}]$		Lower bounds on M_V [TeV]	
Yukawa pair	e–τ	μ–τ	e–τ	μ–τ
$\lvert x_{1,2}^{\ell-\tau}\rvert$	330	1.5	0.055	0.83

Gauge couplings of vector leptoquarks

Vector leptoquarks interaction with the photon depend on their nature → 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 → $\kappa = 0$
  - 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 $\ell_1 \to \ell_2\gamma$

- 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

LQ	$C_{LQ}^{(1),klmn}$	$C_{LQ}^{(3),klmn}$	$C_{LeQu}^{(1),klmn}$	$C_{LeQu}^{(3),klmn}$	C_{Qe}^{klmn}	C_{Lu}^{klmn}	C_{Ld}^{klmn}	C_{eu}^{klmn}	C_{ed}^{klmn}	C_{LedQ}^{klmn}
S_3	$+\frac{3}{4}Y_{3,nl}^{\text{LL}}Y_{3,mk}^{\text{LL}}$	$+\frac{1}{4}Y_{3,nl}^{\text{LL}}Y_{3,mk}^{\text{LL}}$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$
R_2	$\times$	$\times$	$-\frac{1}{2}Y_{2,nk}^{\text{RL}}Y_{2,lm}^{\text{LR}}$	$-\frac{1}{8}Y_{2,nk}^{\text{RL}}Y_{2,lm}^{\text{LR}}$	$-\frac{1}{2}Y_{2,ml}^{\text{LR}}Y_{2,nk}^{\text{LR}}$	$-\frac{1}{2}Y_{2,ml}^{\text{RL}}Y_{2,nk}^{\text{RL}}$	$\times$	$\times$	$\times$	$\times$
$\tilde{R}_2$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$-\frac{1}{2}\tilde{Y}_{2,ml}^{\text{RL}}\tilde{Y}_{2,nk}^{\text{RL}}$	$\times$	$\times$	$\times$
$\tilde{S}_1$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$+\frac{1}{2}\tilde{Y}_{1,nl}^{\text{RR}}\tilde{Y}_{1,mk}^{\text{RR}}$	$\times$
S_1	$+\frac{1}{4}Y_{1,nl}^{\text{LL}}Y_{1,mk}^{\text{LL}}$	$-\frac{1}{4}Y_{1,nl}^{\text{LL}}Y_{1,mk}^{\text{LL}}$	$+\frac{1}{2}Y_{1,mk}^{\text{LL}}Y_{1,nl}^{\text{RR}}$	$-\frac{1}{8}Y_{1,mk}^{\text{LL}}Y_{1,nl}^{\text{RR}}$	$\times$	$\times$	$\times$	$+\frac{1}{2}Y_{1,nl}^{\text{RR}}Y_{1,mk}^{\text{RR}}$	$\times$	$\times$
U_3	$-\frac{3}{2}X_{3,ml}^{\text{LL}}X_{3,nk}^{\text{LL}}$	$+\frac{1}{2}X_{3,ml}^{\text{LL}}X_{3,nk}^{\text{LL}}$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$
V_2	$\times$	$\times$	$\times$	$\times$	$+X_{2,ln}^{\text{LR}}X_{2,km}^{\text{LR}}$	$\times$	$+X_{2,nl}^{\text{RL}}X_{2,mk}^{\text{RL}}$	$\times$	$\times$	$-2X_{2,mk}^{\text{RL}}X_{2,nl}^{\text{LR}}$
$\tilde{V}_2$	$\times$	$\times$	$\times$	$\times$	$\times$	$+\tilde{X}_{2,nl}^{\text{RL}}\tilde{X}_{2,mk}^{\text{RL}}$	$\times$	$\times$	$\times$	$\times$
$\tilde{U}_1$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$-\tilde{X}_{1,ml}^{\text{RR}}\tilde{X}_{1,nk}^{\text{RR}}$	$\times$	$\times$
U_1	$-\frac{1}{2}X_{1,ml}^{\text{LL}}X_{1,nk}^{\text{LL}}$	$-\frac{1}{2}X_{1,ml}^{\text{LL}}X_{1,nk}^{\text{LL}}$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$-X_{1,ml}^{\text{RR}}X_{1,nk}^{\text{RR}}$	$+2X_{1,nk}^{\text{LL}}X_{1,ml}^{\text{RR}}$

Table: Results of the matching of pairs of Yukawa couplings stemming from each leptoquark type to the Wilson coefficients of the four-fermion operators of SMEFT. Notice that, owing to the Fierz rearrangement, we also obtain contributions containing tensorial operators, i.e. $C_{LeQu}^{(3)}$.

$C_\gamma/\Lambda^2_{\rm CLFV}$	Upper bounds on $\frac{|yy'|}{M_S^2}$ $[10^{-3}\,\mathrm{TeV}^{-2}]$		Lower bounds on M_S [TeV]	
Yukawa pair	Belle	Belle II	Belle	Belle II
$|y_{2\,\tau}^{\rm RL} y_2^{\rm LR}|$	150	19	3.1	8.6
$|y_{1\,\tau}^{\rm LL} y_1^{\rm RR}|$	21	2.7	8.2	23

$\tau \to \ell\gamma$	Upper bounds on $\frac{|yy'|}{M_S^2}$ $[10^{-3}\,\mathrm{TeV}^{-2}]$		Lower bounds on M_S [TeV]	
Yukawa pair	$\tau \to e\gamma$	$\tau \to \mu\gamma$	$\tau \to e\gamma$	$\tau \to \mu\gamma$
$|y_{2\,\tau}^{\rm RL} y_2^{\rm LR}|$	0.66	0.79	83	75
$|y_{1\,\tau}^{\rm LL} y_1^{\rm RR}|$	1.4	1.7	71	64