Effects of scalar leptoquarks S_1 and R_2 on charged lepton flavor violating decays $\tau \to \ell_n \ell_n \ell_m^c$ $(\ell = e, \mu)$.

Juan Pablo Hoyos D.

Department of Physics, Cinvestav.

In collaboration with: **G. Hernández T., O. Miranda R., R. Sánchez V.**

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Introduction

The SM is a non-Abelian gauge QFT invariant under the symmetry group $\mathcal{G}_{\mathsf{SM}} = \mathsf{SU}(3)_C \otimes \mathsf{SU}(2)_L \otimes \mathsf{U}(1)_Y$, which incorporates spontaneous symmetry breaking. It provides a highly successful description of the dynamics of all known elementary particles to date.

Open theoretical and experimental questions in the Standard Model remain under active investigation.

- Neutrino masses.
- Baryon asymmetry inte universe (BAU).
- Dark matter.
- Hierarchy problem.

CLFV processes are highly suppressed in the SM, making their study especially attractive in BSM models.

What are LQs?

Leptoquarks (LQs) are hypothetical bosons, either scalar or vector, that unify the properties of quarks and leptons.

> The main feature of leptoquarks is their ability to turn leptons into quarks and vice versa.

Here, we focus on scalar leptoquarks only.

What are LQs?

The table below shows how scalar LQs transform under $\mathcal{G}_{SM}$.

- I. Bigaran and R. R. Volkas, Phys. Rev. D **105** (2022) no.1, 015002.

Scalar LQs	$\mathcal{G}_{SM}$	Mc	F
S_3	$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	✗	-2
R_2	$(\mathbf{3}, \mathbf{2}, 7/6)$	✓	0
$\tilde{R}_2$	$(\mathbf{3}, \mathbf{2}, 1/6)$	✗	0
$\tilde{S}_1$	$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	✗	-2
S_1	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✓	-2

Tabla: LQ representations under $\mathcal{G}_{SM}$ and fermion number F. Subscripts indicate SU$(2)_L$ representations, and tildes ($\sim$) distinguish LQs with the same SU$(2)_L$ representation but different hypercharges.

Processes, $\tau(p) \to \ell_n(p_1)\ell_n(p_2)\ell_m^c(p_3)$

Examples include the following channels: $\tau^- \to \mu^-\mu^-e^+$ and $\tau^- \to e^-e^-\mu^+$.

$$\mathcal{L}_{F=0} = \bar{q}_j \left(\lambda_L^{jk*} P_L + \lambda_R^{jk*} P_R\right) \ell_k R_2 + \text{h.c.},$$
$$\mathcal{L}_{|F|=2} = \overline{q_j^c} \left(\lambda_L^{jk} P_L + \lambda_R^{jk} P_R\right) \ell_k S_1 + \text{h.c.} \quad (1)$$

- I. Doršner, S. Fajfer, A. Greljo, J. F. Kamenik and N. Košnik, Phys. Rept. **641** (2016), 1-68.

At the 1-loop level, these processes receive contributions only from box-type diagrams.

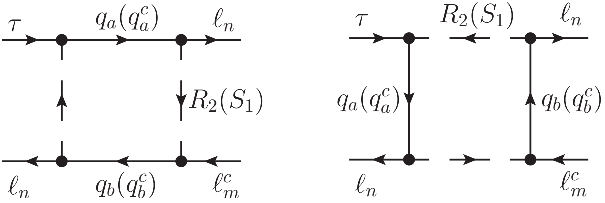

Figura: Box diagrams contributing to the decay $\tau \to \ell_n\ell_n\ell_m^c$, where $q_{a,b}$ are up-type quarks with $a, b = 1, 2, 3$.

Processes, $\tau(p) \to \ell_n(p_1)\ell_n(p_2)\ell_m^c(p_3)$

After calculating the amplitudes, the following branching ratios for the mentioned processes are obtained:

$$\mathrm{BR}_{|F|=2} = \frac{m_\tau^5}{512\pi^3\Gamma_\tau}\left\{\frac{1}{24}\left(|S_{LR}|^2 + |S_{RL}|^2\right) + \frac{1}{6}\left(|S_{LL}|^2 + |S_{RR}|^2 + |V_{LL}|^2 + |V_{RR}|^2 + |V_{LR}|^2 + |V_{RL}|^2\right)\right\}, \tag{2}$$

$$\mathrm{BR}_{F=0} = \frac{m_\tau^5}{512\pi^3\Gamma_\tau}\left\{\frac{1}{6}\left(|S_{LL}|^2 + |S_{RR}|^2 + |V_{LL}|^2 + |V_{RR}|^2\right) + \frac{1}{12}\left(|S_{LR}|^2 + |S_{RL}|^2\right)\right\}. \tag{3}$$

Processes, $\tau(p) \to \ell_n(p_1)\ell_n(p_2)\ell^c_m(p_3)$

For example, in the case of $\mathrm{BR}_{F=0}$

$$S_{LR} = \frac{N_c}{16\pi^2}\sum_{a,b}\lambda_L^{ai*}\lambda_R^{bm*}\left(\lambda_L^{bn}\lambda_R^{an}m_{q_a}m_{q_b}D_0 - 2\lambda_L^{an}\lambda_R^{bn}D_{00}\right),$$

In the amplitude: $S_{LR}[\bar{u}(p_1)P_L u(p)][\bar{u}(p_2)P_R v(p_3)]$. (4)

The expression for S_{RL} is obtained by swapping $L \leftrightarrow R$. D_0 and D_{00} are Passarino-Veltman functions.

Restrictions from Δa_μ and $\ell_i \to \ell_n \gamma$.

Leptoquarks give rise to new loop-level contributions to the $\ell\ell\gamma$ vertex. In the LQ scenario, we have:

$$\Delta a_\ell = a_\ell^{\mathsf{Exp}} - a_\ell^{\mathsf{SM}} = -\frac{N_c m_\ell^2}{16\pi^2 M_{LQ}^2} \sum_q \left\{ \left(|\lambda_L^{q\ell}|^2 + |\lambda_R^{q\ell}|^2 \right) \mathcal{A}_1(q) + \frac{m_q}{m_\ell} \mathrm{Re}(\lambda_L^{q\ell} \lambda_R^{q\ell *}) \mathcal{A}_2(q) \right\}, \quad (5)$$

$$\mathcal{A}_1(q) = Q_q F_1(x_q) + Q_{LQ} F_2(x_q), \quad \mathcal{A}_2(q) = Q_q F_3(x_q) + Q_{LQ} F_4(x_q)$$

- R. Mandal and A. Pich, JHEP **12** (2019), 089.

R_2	S_1
$\mathrm{Re}(\lambda_L^{32} \lambda_R^{32*}) \in [-6.6, 1.6] \times 10^{-4}$	$\mathrm{Re}(\lambda_L^{32} \lambda_R^{32*}) \in [-10.6, 2.6] \times 10^{-4}$
$\mathrm{Re}(\lambda_L^{22} \lambda_R^{22*}) \in [-23, 5.6] \times 10^{-3}$	$\mathrm{Re}(\lambda_L^{22} \lambda_R^{22*}) \in [-25, 6.2] \times 10^{-3}$

Tabla: 1σ ranges of $\lambda_L^{q2} \lambda_R^{q2*}$ for R_2 and S_1, with $M_{LQ} = 1$ TeV and $\Delta a_\mu = (38 \pm 63) \times 10^{-11}$. For $M_{LQ} > 1$ TeV, the values scale as $(M_{LQ}/\mathrm{TeV})^2$.

Restrictions from Δa_μ and $\ell_i \to \ell_n\gamma$.

The branching ratio of the decays $\ell_i \to \ell_n\gamma$ induced by LQs is given by

$$\text{BR}\left(\ell_i \to \ell_n\gamma\right) = \frac{\alpha_{em}}{4\Gamma_{\ell_i}} \frac{\left(m_{\ell_i}^2 - m_{\ell_n}^2\right)^3}{m_{\ell_i}^3} \sum_q \left(|A_R^{qin}|^2 + |A_L^{qin}|^2\right),$$

$$A_R^{qin} = \frac{N_c}{32\pi^2 M_{\text{LQ}}^2}\left\{\left(m_{\ell_i}\lambda_L^{qi}\lambda_L^{qn*} + m_{\ell_n}\lambda_R^{qi}\lambda_R^{qn*}\right)\mathcal{A}_1(q)\right. \quad (6)$$

$$\left. + m_q\left(\lambda_L^{qi}\lambda_R^{qn*}\right)\mathcal{A}_2(q)\right\}, \qquad A_L^{qin} = A_R^{qin}(R \leftrightarrow L).$$

- R. Mandal and A. Pich, JHEP **12** (2019), 089.

LQ	BR($\mu \to e\gamma$)	BR($\tau \to e\gamma$)	BR($\tau \to \mu\gamma$)
R_2	$\lvert\lambda_{LR}^{321}\rvert^2 < 1.1 \times 10^{-15}$	$\lvert\lambda_{LR}^{331}\rvert^2 < 1.4 \times 10^{-7}$	$\lvert\lambda_{LR}^{332}\rvert^2 < 1.8 \times 10^{-7}$
	$\lvert\lambda_{LR}^{221}\rvert^2 < 1.3 \times 10^{-12}$	$\lvert\lambda_{LR}^{231}\rvert^2 < 1.6 \times 10^{-4}$	$\lvert\lambda_{LR}^{232}\rvert^2 < 2.2 \times 10^{-4}$
S_1	$\lvert\lambda_{LR}^{321}\rvert^2 < 2.9 \times 10^{-15}$	$\lvert\lambda_{LR}^{331}\rvert^2 < 3.6 \times 10^{-7}$	$\lvert\lambda_{LR}^{332}\rvert^2 < 4.8 \times 10^{-7}$
	$\lvert\lambda_{LR}^{221}\rvert^2 < 1.7 \times 10^{-12}$	$\lvert\lambda_{LR}^{231}\rvert^2 < 2.1 \times 10^{-4}$	$\lvert\lambda_{LR}^{232}\rvert^2 < 2.8 \times 10^{-4}$

Tabla: Bounds on the combination $|\lambda_{LR}^{qin}|^2 \equiv |\lambda_L^{qi}\lambda_R^{qn*}|^2 + |\lambda_R^{qi}\lambda_L^{qn*}|^2$, with $M_{LQ} = 1$ TeV. For $M_{LQ} > 1$ TeV, $|\lambda_{LR}^{qin}|^2 \sim (M_{LQ}/\text{TeV})^4$.

Results and numerical analysis

If $\lambda^{q\ell}_{L,R}$ are reals, the R_2 and S_1 representations have 18 free parameters. We consider the following scenarios to simplify the analysis:

- Top-only flavor structure. $\lambda^{3\ell}_{L,R}$.
- Charm-only flavor structure. $\lambda^{2\ell}_{L,R}$.

$$\lambda^{3\ell}_{L,R} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \lambda^{31}_{L,R} & \lambda^{32}_{L,R} & \lambda^{33}_{L,R} \end{pmatrix}, \quad \lambda^{2\ell}_{L,R} = \begin{pmatrix} 0 & 0 & 0 \\ \lambda^{21}_{L,R} & \lambda^{22}_{L,R} & \lambda^{23}_{L,R} \\ 0 & 0 & 0 \end{pmatrix}.$$

We also assume that $\lambda^{q\ell}_{L,R}$ are subject to the perturbative upper bound

$$0 < \lambda^{q\ell}_{L,R} < \sqrt{4\pi}. \tag{7}$$

Results and numerical analysis

By performing a random scan over the parameters $\lambda^{q\ell}_{L,R}$ with $M_{LQ} = 1$ TeV, a region of the parameter space satisfying the above constraints is:

$$
\begin{aligned}
\lambda_L^{q1} &= [10^{-12}, 10^{-10}], &\quad \lambda_R^{q1} &= [10^{-5}, 10^{-1}],\\
\lambda_L^{q2} &= [0, 10^{-3}], &\quad \lambda_R^{q2} &= [10^{-2}, \sqrt{4\pi}],\\
\lambda_L^{q3} &= [10^{-5}, 10^{-4}], &\quad \lambda_R^{q3} &= [0, \sqrt{4\pi}].
\end{aligned}
\tag{8}
$$

Results and numerical analysis

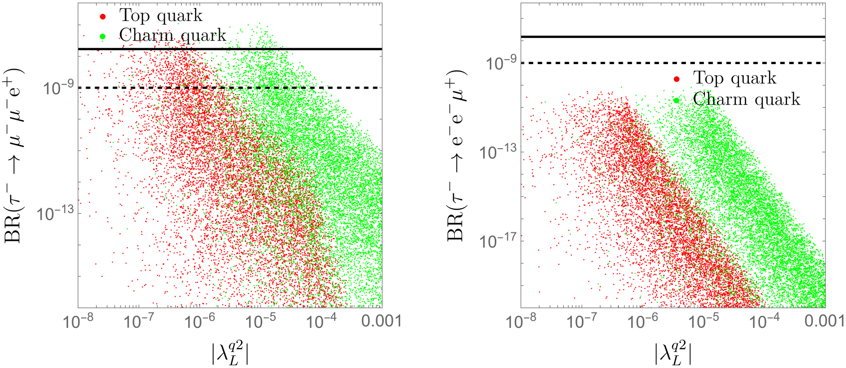

Figura: Region of the parameters $|\lambda_L^{q2}|$. The branching ratios correspond to S_1. Similar regions are obtained in the R_2 model. The solid (dashed) black line represents the current (future) limit of the process.

Results and numerical analysis

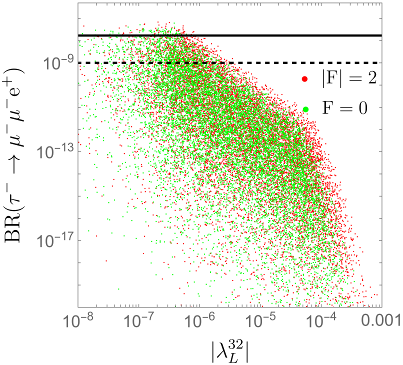

Figura: Parameter space of $|\lambda_L^{32}|$ for the two channels $\tau \to \ell_n \ell_n \ell_m^c$, for the LQs S_1 ($|F| = 2$) and R_2 ($F = 0$).

Conclusions

- We have studied the low-energy processes $\tau \to \ell_n \ell_n \ell_m^c$ within the scalar leptoquark models R_2 and S_1, providing a complementary analysis of CLFV processes.

- We derived analytical expressions for the BRs in both models. The analisys of parameter space is done using two specific flavor structures for $\lambda_{L,R}^{q\ell}$, and including constraints from Δa_μ and $\ell_i \to \ell_n \gamma$ processes.

Conclusions

- Numerical results indicate that, within the allowed $\lambda^{q\ell}_{L,R}$ ranges, there are regions of parameter space where the observation of $\tau \to \ell_n \ell_n \ell^c_m$ could be within reach of current or near-future experimental sensitivities.

- Among the models studied, signals from both the lepton number conserving and lepton number violating scenarios are equally accessible, preventing the exclusion of the LNV model.

¡Thank you for your attention!