Lepton Flavor Violation in a Z' model for the $b \to s$ anomalies

Paulina Rocha-Morán

BCTP und Physikalisches Institut
University of Bonn

arXiv:1810.02135
(in collab. with Avelino Vicente)

29.11.2018

Outline

The b $\to$ s anomalies

2013: First anomalies found by LHCb.

- Decrease in several branching ratios.
- Several anomalies in angular observables (P'_5).

2015: 'Confirmed' using full LHC run I dataset

2014/2017$^{(*)}$: Lepton Flavor Universality Violation

$$R_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}, \qquad [R_{K^{(*)}}]^{SM} \sim 1$$

LHCb measurement

$[R_K] = 0.745^{+0.090}_{-0.074} \pm 0.036$, $q^2 \in [1, 6]$ GeV^2

$[R_{K^*}] = 0.660^{+0.110}_{-0.070} \pm 0.024$, $q^2 \in [0.045, 1.1]$ GeV^2

$[R_{K^*}] = 0.685^{+0.113}_{-0.069} \pm 0.047$, $q^2 \in [1.1, 6.0]$ GeV^2

The b $\rightarrow$ s anomalies

2013: First anomalies found by LHCb.

- Decrease in several branching ratios.
- Several anomalies in angular observables (P_5').

2015: 'Confirmed' using full LHC run I dataset

2014/2017$^{(*)}$: Lepton Flavor Universality Violation

$$R_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}, \qquad [R_{K^{(*)}}]^{SM} \sim 1$$

LHCb measurement

$[R_K] = 0.745^{+0.090}_{-0.074} \pm 0.036$, $q^2 \in [1, 6]$ GeV^2

$[R_{K^*}] = 0.660^{+0.110}_{-0.070} \pm 0.024$, $q^2 \in [0.045, 1.1]$ GeV^2

$[R_{K^*}] = 0.685^{+0.113}_{-0.069} \pm 0.047$, $q^2 \in [1.1, 6.0]$ GeV^2

The effective Hamiltonian for $b \to s$ transitions

$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}}\, V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right) + \text{h.c.}\,, \qquad (1)$$

The relevant effective operators for the study of the $B \to K \ell^+ \ell^-$ decay are

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)\left(\bar{\ell}\gamma^\mu \ell\right), \quad \mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)\left(\bar{\ell}\gamma^\mu \gamma_5 \ell\right) \qquad (2)$$

It is convenient to split their associated Wilson coefficients into the SM and NP contributions $C_k = C_k^{\rm SM} + C_k^{\rm NP}$.

Global fits to $b \to s$ data require a negative $C_9^{\mu\mu,NP}$ contribution, leading to a total $C_9^{\mu\mu}$ significantly smaller than the one in the SM.

$$C_9^{\mu\mu,NP} \to [-0.88, -0.37] \text{ at } 2\sigma^{[1]}, \quad C_9^{\mu\mu,SM} = 4.07^{[2]}$$

[1] B. Capdevila et al. JHEP 1801 (2018) 093, 1704.05340
[2] S. Descotes-Genon et al. JHEP 1606 (2016) 092, 1510.04239

Outline

Flavor universality and LFV

[3] S. L. Glashow et al. Phys. Rev. Lett. 114 (2015) 091801, 1411.0565

It has been pointed out[3] that Lepton Flavor Universality Violation implies Lepton Flavor Violation

This observation motivates the search of LFV in B meson decays.

Outline

The model[4]

extension of:
[4] D. Aristizabal et al. Phys. Rev. D92 (2015) 015001, 1503.06077

New $U(1)_x$ gauge group

	spin	generations	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
H	0	1	2	1/2	0
ϕ	0	1	1	0	2
S	0	1	1	0	−4
ℓ_L	1/2	3	2	−1/2	0
q_L	1/2	3	2	1/6	0
$L_{L,R}$	1/2	2	2	−1/2	2
$Q_{L,R}$	1/2	1	2	1/6	2
$F_{L,R}$	1/2	2	1	0	2

$$L_{L,R} = \begin{pmatrix} N \\ E \end{pmatrix}_{L,R}, \qquad Q_{L,R} = \begin{pmatrix} U \\ D \end{pmatrix}_{L,R}.$$

Dirac mass

$$\mathcal{L}_m = m_Q \overline{Q}Q + m_L \overline{L}L + m_F \overline{F}F. \tag{3}$$

The Yukawa terms involved in flavor physics

$$\mathcal{L}_Y = \lambda_Q \overline{Q_R}\phi q_L + \lambda_L \overline{L_R}\phi \ell_L + y\,\overline{L_L}HF_R + \widetilde{y}\,\overline{L_R}HF_L + h\,S\overline{F_L^c}F_L + \widetilde{h}\,S\overline{F_R^c}F_R + \text{h.c.}\,, \tag{4}$$

Symmetry breaking and scalar spectrum

The scalar potential has the form

$$\mathcal{V} = \mathcal{V}_{\boldsymbol{SM}} + \mathcal{V}(H,\phi,S) + \mathcal{V}(\phi,S)\,, \tag{5}$$

$$\mathcal{V}(H,\phi,S) = \lambda_{\boldsymbol{H\phi}}\,|H|^2|\phi|^2 + \lambda_{\boldsymbol{HS}}\,|H|^2|S|^2\,, \tag{6}$$

$$\mathcal{V}(\phi,S) = m_\phi^2|\phi|^2 + m_{\boldsymbol{S}}^2|S|^2 + \frac{\lambda_\phi}{2}|\phi|^4 + \frac{\lambda_{\boldsymbol{S}}}{2}|S|^4 + \lambda_{\phi\boldsymbol{S}}\,|\phi|^2|S|^2 + \left(\mu'\phi^2\,S + \text{h.c.}\right) \tag{7}$$

All the scalars acquire a VEV

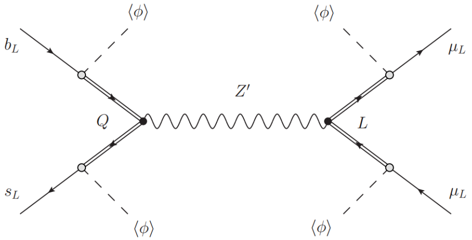
$$\langle H^0\rangle = \frac{v}{\sqrt{2}}\,, \qquad \langle\phi\rangle = \frac{v_\phi}{\sqrt{2}}\,, \qquad \langle S\rangle = \frac{v_S}{\sqrt{2}}\,. \tag{8}$$

$\langle\phi\rangle \neq 0$ and $\langle S\rangle \neq 0$ will be responsible for the SSB of $U(1)_X$, giving

$$\rightarrow m_{Z'}^2 = 4g_X^2\left(v_\phi^2 + 4v_S^2\right) \tag{9}$$

and for inducing mixings between V-L fermions and their SM counterparts.

The mixing leads to an effective coupling of the Z' to the SM fermions.



$$\Delta_L^{bs} = \frac{2g_X \lambda_Q^b \lambda_Q^{s*} v_\phi^2}{2m_Q^2 + \left(|\lambda_Q^s|^2 + |\lambda_Q^b|^2\right) v_\phi^2}, \qquad (10)$$

$$\Delta_L^{\mu\mu} = 2g_X \left(|U_{L_{42}}|^2 + |U_{L_{52}}|^2\right) \qquad (11)$$

U_L Left matrix of biunitarity diagonalization of ℓ-L mass matrix.

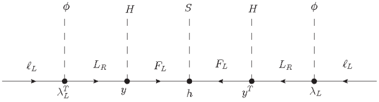
$$C_9^{\mu\mu,NP} = -C_{10}^{\mu\mu,NP} = -\frac{\Delta_L^{bs}\Delta_L^{\mu\mu}}{V_{tb}V_{ts}^*}\left(\frac{\Lambda_\nu}{m_{Z'}}\right)^2, \qquad (12)$$

$$\Lambda_v = \left(\frac{\pi}{\sqrt{2}G_F\alpha}\right)^{1/2} \simeq 4.94 \text{ TeV} \qquad (13)$$

Neutrino mass

The complete 11×11 neutral fermion mass matrix in the basis $\psi^0 = \{\nu_L, N_R^c, N_L, F_R^c, F_L\}$

$$\mathcal{M} = \begin{pmatrix} 0 & -\frac{\lambda_L^T v_\phi}{\sqrt{2}} & 0 & 0 & 0 \\ -\frac{\lambda_L v_\phi}{\sqrt{2}} & 0 & m_L^T & 0 & \frac{\widetilde{y} v}{\sqrt{2}} \\ 0 & m_L & 0 & -\frac{y v}{\sqrt{2}} & 0 \\ 0 & 0 & -\frac{y^T v}{\sqrt{2}} & \sqrt{2}\,\widetilde{h} v_S & m_F^T \\ 0 & \frac{\widetilde{y}^T v}{\sqrt{2}} & 0 & m_F & \sqrt{2}\, h v_S \end{pmatrix}$$



◇ $\mathcal{M}$ can be diagonalized through an *inverse seesaw approximation* (ISS) by assuming

$$h v_S, \widetilde{h} v_S \ll y v, \widetilde{y} v, \lambda_L v_\phi \ll m_{L,F}$$

◇ $\widetilde{y} = \widetilde{h} = 0$, since they do not contribute to the generation of neutrino masses at leading order.

◇ 3×3 mass matrix for the light neutrinos.

$$\mathcal{M}_\nu \simeq \frac{v^2 v_\phi^2 v_S}{2\sqrt{2}} \lambda_L^T\, m_L^{-1}\, y\, m_F^{-1}\, h\, \left(m_F^{-1}\right)^T\, y^T\, \left(m_L^{-1}\right)^T \lambda_L \,. \qquad (14)$$

Outline

Phenomenological analysis of LFV observables

[5] Porod, Werner et al. Eur.Phys.J. C74 (2014) no.8, 2992
[6] D. V. Forero, et al. Phys. Rev. D90, 093006 (2014), 1405.7540

Computation of LFV observables: SARAH ↓ FlavorKit[5] ⇒ SPheno

Model parameters relevant for flavor processes

- V-L fermion masses m_Q, m_L, m_F.
- Yukawa couplings λ_Q, λ_L, y.
- VEV v_S, mass $m_{Z'}$ and gauge coupling g_X. v_ϕ is obtained by eq. (9)

h is fixed to give the correct neutrino masses according to neutrino oscillation data[6]

$$h = \bar{v}^{-5}\, m_F\, y^{-1}\, m_L\, \bar{\lambda}_L^T\, m_\nu\, \bar{\lambda}_L\, m_L^T\, \left(y^{-1}\right)^T\, m_F^T\,, \tag{15}$$

where $\bar{\lambda}_L$ is a 3×2 matrix such that $\lambda_L \bar{\lambda}_L = \mathbb{I}_2$.

Phenomenological analysis

- Solve tadpole eqs. for m_H^2, m_ϕ^2 and m_S^2.
- Compute couplings h (eq. 15)
  - $\hookrightarrow$ Best fit neutrino oscillation data.
  - $\hookrightarrow$ Dirac phase $\delta = 0$.
  - $\hookrightarrow$ Normal hierarchy.
- Fix the scalar potential parameters

λ_L structure forbids contribution to electron observables.

$$\lambda_L = \begin{pmatrix} 0 & 1.0 & x \\ 0 & x & 1.0 \end{pmatrix} \tag{16}$$

B_s-$\bar{B}_s$ mixing constrain

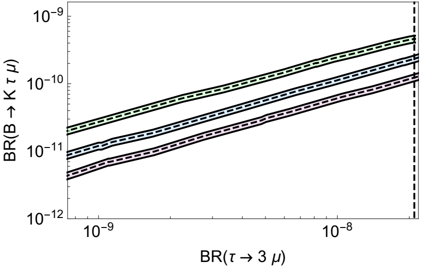
$$\frac{m_{Z'}}{|\Delta_L^{bs}|} \gtrsim 244\,\text{TeV}\,. \tag{17}$$

LHC direct searches are taken into account to constraint the V-L fermion masses.

Outline

$$\frac{\text{BR}(B \to K \tau \mu)}{\text{BR}(\tau \to 3\,\mu)} = 1.7 \cdot 10^7 \text{ TeV}^4 \left(\frac{\left|\Delta_L^{bs}\right|}{m_{Z'}} \right)^4 \frac{1}{\left|C_9^{\mu\mu,\text{NP}}\right|^2} . \qquad (18)$$

	g_X	v_S	$m_{Z'}$	$(m_L)_{11} = (m_L)_{22}$	$(\lambda_Q)_2 = (\lambda_Q)_3$
Green	0.155	10.6 GeV	1592 GeV	1904 GeV	0.0407
Blue	0.2	200 GeV	1010 GeV	1600 GeV	0.055
Purple	0.4	34 GeV	2330 GeV	1007 GeV	0.052

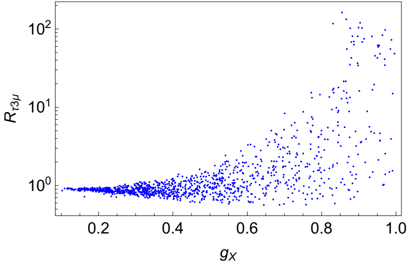


$$\text{BR}(B \to K \tau \mu)_{\text{max}} \lesssim 8 \cdot 10^{-10} .$$

P. Rocha-Morán, A. Vicente, arXiv:1810.02135

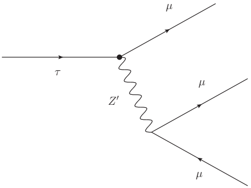
On the relevance of loop effects in BR($\tau \to 3\,\mu$)

$$R_{\tau 3\mu} = \frac{\text{BR}(\tau \to 3\,\mu)_{\text{tree-level}}}{\text{BR}(\tau \to 3\,\mu)_{\text{1-loop}}}$$

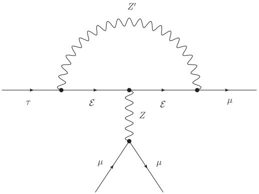


$$0.05 < g_X < 1.0$$
$$10\text{ GeV} < v_S < 500\text{ GeV}$$
$$0.01 < (\lambda_Q)_2 = (\lambda_Q)_3 < 0.1$$
$$0.8\text{ TeV} < (m_L)_{11} = (m_L)_{22} < 2\text{ TeV}$$
$$1\text{ TeV} < m_{Z'} < 3\text{ TeV}$$

$$\mathcal{A}_{\text{tree}} = g_X^2 / m_{Z'}^2\, F_{\text{tree}}\,(V_e)$$



$$\mathcal{A}_{\text{loop}} = \frac{1}{16\pi^2}\,\frac{g_X^2\, g_{Z\ell\ell}}{m_Z^2}\, F_{\text{loop}}^{g_X}\,(m_{\mathcal{E}}, V_e)$$



Loop effects are negligible when $g_X \lesssim 0.4$

Outline

Conclusions

- The additional d.o.f. involved in neutrino masses and mixings play a sub-dominant role in the LFV predictions of the model, which are dominated by the NP effects induced by the states responsible for the explanation of the $b \to s$ anomalies.
- $B \to K\tau\mu$ and $\tau \to 3\,\mu$ are dominated by tree-level Z' boson exchange. We derived the upper limit $\text{BR}(B \to K\tau\mu)_{\text{max}} \lesssim 8 \cdot 10^{-10}$. This limit applies to all models with purely left-handed Z' couplings.
- Loop effects in $\tau \to 3\,\mu$ may be comparable to the tree-level ones. This is due to the strong suppression induced by the tree-level exchange of a TeV-scale Z' boson, which is absent in many 1-loop contributions. In fact, this feature is expected in generic Z' models for the $b \to s$ anomalies.


THE FLAVOR CHANGER
Thank you!