# Lepton Flavor Violation in $b \to s\ell_i\ell_j$

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## Motivation

- Lepton flavor universality ratios $\boldsymbol{R_K}$ and $\boldsymbol{R_{K^*}}$, as well as $B_s \to \ell_i\ell_j$, $(\ell_{i,j} \in \{e,\mu,\tau\})$ are theoretically clean observables.

$$R_{K^{(*)}} = \left.\frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}\right|_{q^2\in[1,6]\,\mathrm{GeV}^2} \qquad R_{K^*}^{[0.042,1]} = \left.\frac{\mathcal{B}(B \to K^{*}\mu^+\mu^-)}{\mathcal{B}(B \to K^{*}e^+e^-)}\right|_{q^2\in[0.042,1]\,\mathrm{GeV}^2}$$

- All three have been measured to be **smaller** than predicted in the SM.
- These hints of **Lepton Flavor Universality Violation** (LFUV) observed in B meson decays point to physics beyond the standard model
- To explain these deviations, one needs to invoke a scenario of physics beyond the standard model.
- In most of the NP scenarios, **LFUV ⇒ LFV**
- We combine low energy observables, B anomalies the high-$p_T$ tails $pp \to \ell_i\ell_j$ and constrain the Wilson coefficients of the effective theory describing $B_s \to \ell_i\ell_j$ transitions

## EFT for $b \to s\ell_i\ell_j$

- By using OPE at low energies, dimension 6 operators are dominant
- To describe the low energy observables, we can do an **OPE** at dimension 6, including all possible flavor structure
- Loop induced in the SM (only for $i = j$)

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_{a=9,10,\ldots} \left( C_a^{ij}(\mu)\mathcal{O}_a^{ij}(\mu) + C_a^{ij\prime}(\mu)\mathcal{O}_a^{ij\prime}(\mu) \right) + \mathrm{h.c.}$$

$$\mathcal{O}_9^{ij(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}_i\gamma^\mu\ell_j), \qquad \mathcal{O}_{10}^{ij(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}_i\gamma^\mu\gamma^5\ell_j),$$

$$\mathcal{O}_S^{ij(\prime)} = (\bar{s}P_{R(L)} b)(\bar{\ell}_i\ell_j), \qquad \mathcal{O}_P^{ij(\prime)} = (\bar{s}P_{R(L)} b)(\bar{\ell}_i\gamma^5\ell_j),$$

- Accommodating B-anomalies $R_{K^{(*)}}$ requires modifying $\boldsymbol{C_9^{\mu\mu}}$ and/or $\boldsymbol{C_{10}^{\mu\mu}}$.
- N.B. in the SM, all Wilson Coefficients (WCs) $\boldsymbol{C_a^{ij} = 0}$ for $\boldsymbol{i \neq j}$.
- For the exclusive modes Hb->Hs l1 l2, evaluating amplitude requires knowledge of hadronic matrix elements.
- Exclusive modes $B \to K\ell_i\ell_j, B \to K^*\ell_i\ell_j, B_s \to \ell_i\ell_j$, were studied before.
- We provide full expression for $\Lambda_b \to \Lambda\ell_i\ell_j$ currently studied by LHCb.
- Amplitude $\langle\Lambda_b|\mathcal{H}^{\rm eff}|\Lambda\rangle$ requires knowledge of hadronic matrix **Form Factors:**

$$\langle\Lambda_b|\Gamma|\Lambda\rangle \propto f_0, f_+, f_\perp, g_0, g_+, g_\perp$$

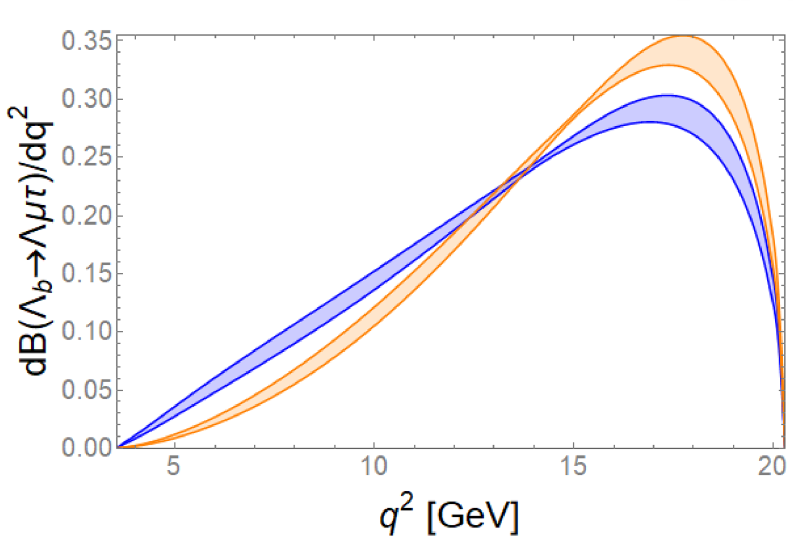
All known in lattice QCD for the following processes:

- We computed

$$\frac{d^2\Gamma(\Lambda_b \to \Lambda\bar{\ell}_i\ell_j)}{dq^2 d\cos\theta} = \frac{|K|^2}{256\pi^3 m_{\Lambda_b}^3}\frac{1}{q^2}\frac{\sqrt{s_+s_-}}{2}\frac{\sqrt{r_+r_-}}{2}\sum_{16\ \rm spins}|\mathcal{M}|^2,$$

$$= \sum_s \left(a_s + b_s\cos\theta + c_s\cos^2\theta\right),$$

Functions of $\boldsymbol{q^2}$ (momentum transfer), **FFs** and **WCs**




Normalized shape of the differential branching fraction of $\boldsymbol{\Lambda_b \to \Lambda\mu\tau}$ if NP enters only through **vector** (blue) or **scalar** (orange).

- Prediction concerning LFV decay modes. We find:

 - If NP comes from the **scalar** sector only ($C_S^{ij} \neq 0$, $C_P^{ij} \neq 0$)

$$\mathcal{B}(B \to K^*\ell_i\ell_j) < \mathcal{B}(\Lambda_b \to \Lambda\ell_i\ell_j) < \mathcal{B}(B \to K\ell_i\ell_j) < \mathcal{B}(B_s \to \ell_i\ell_j)$$

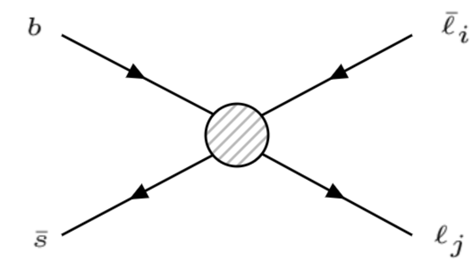
 - If NP comes from the **vector** sector only ($C_9^{ij} \neq 0$, $C_{10}^{ij} \neq 0$)

$$\mathcal{B}(B_s \to \ell_i\ell_j) < \mathcal{B}(B \to K\ell_i\ell_j) < \mathcal{B}(\Lambda_b \to \Lambda\ell_i\ell_j) \approx \mathcal{B}(B \to K^*\ell_i\ell_j)$$

LHCb currently working on: $\boldsymbol{\Lambda_b \to \Lambda\mu e}$
In the future: $\boldsymbol{\Lambda_b \to \Lambda\tau\mu}$

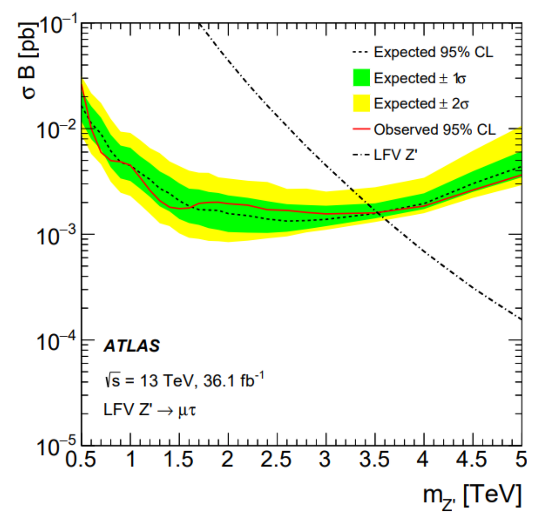
## LFV in dilepton tails at LHC

- Bounds on the WCs can be obtained from the studies of the high-$p_T$ tails of at LHC.
- Partonic cross-section:



$$[\hat\sigma(\hat s)]_{ij} = \frac{\hat s}{144\pi v^4}\sum_{\alpha\beta} C_\alpha^{ij} C_\beta^{ij} M_{\alpha\beta},$$

where $M$ is a mostly diagonal matrix, so that the WCs $C_\alpha^{ij}$ can be probed individually.




- We used the experimental limits on $Z' \to \ell_1\ell_2$ and recast them to the bound on our WCs.
- Current (36 fb$^{-1}$) and projected (3 ab$^{-1}$) 2σ limits on the WC:

| | $bs \to e\mu$ | $bs \to e\tau$ | $bs \to \mu\tau$ |
|---|---|---|---|
| $\lvert C_9^{ij} \pm C_{10}^{ij}\rvert \times 10^3$ | 9.9(3.7) | 34(9) | 37(11) |
| $\lvert C_S^{ij} \pm C_P^{ij}\rvert \times 10^3$ | 11.4(4.3) | 39(10) | 43(13) |

- We see that direct searches are not competitive with low-energy experiment
- For example, assuming $C_9^{\mu\tau} = -C_{10}^{\mu\tau}$:

| Process | Projected LHC limit (3 ab$^{-1}$) | L.E. exp limit |
|---|---|---|
| $\mathcal{B}(B_s \to \tau^\pm\mu^\mp)$ | $2.5 \times 10^{-4}$ | $4.2 \times 10^{-5}$ |
| $\mathcal{B}(B \to K\tau^\pm\mu^\mp)$ | $5.3 \times 10^{-4}$ | $3.9 \times 10^{-5}$ |
| $\mathcal{B}(B \to K^*\tau^\pm\mu^\mp)$ | $8.9 \times 10^{-4}$ | $N.A.$ |
| $\mathcal{B}(\Lambda_b \to \Lambda\tau^\pm\mu^\mp)$ | $8.9 \times 10^{-4}$ | $N.A.$ |

## Example of an explicit model: Low Energy Z'

- Z-like $\mathcal{O}(1\ \mathrm{TeV})$ boson with non-diagonal flavor structure:

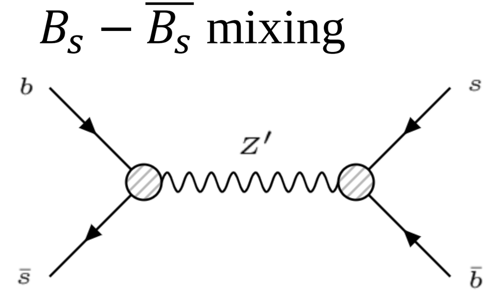
$$\mathcal{L}_{Z'} \supset g^L_{\ell_i\ell_j}\bar\ell_i\gamma^\mu P_L\ell_j Z'_\mu + g^L_{sb}\bar s\gamma^\mu P_L b Z'_\mu + (L \longleftrightarrow R),$$

- Matching to the EFT results:

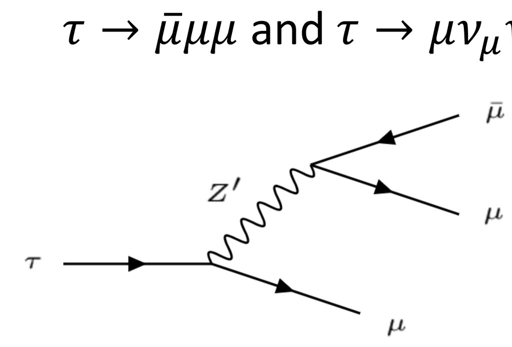
$$C_9^{(\prime)\mu\tau} = -\frac{\pi}{\sqrt{2}m_{Z'}^2}\frac{1}{\alpha G_F V_{tb}V_{ts}^*} g_{sb}^{L(R)}\left(g^R_{\mu\tau} + g^L_{\mu\tau}\right),$$

$$C_{10}^{(\prime)\mu\tau} = -\frac{\pi}{\sqrt{2}m_{Z'}^2}\frac{1}{\alpha G_F V_{tb}V_{ts}^*} g_{sb}^{L(R)}\left(g^R_{\mu\tau} - g^L_{\mu\tau}\right),$$

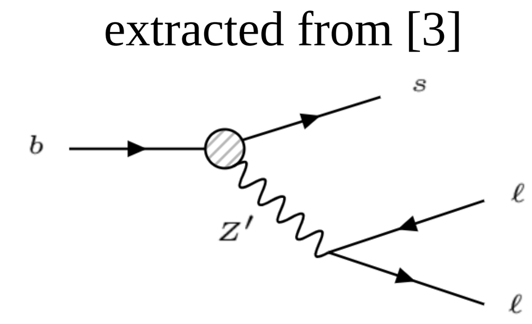
Can be extracted from $B_s - \overline{B_s}$ mixing



Can be extracted from $\tau \to \bar\mu\mu\mu$ and $\tau \to \mu\nu_\mu\nu_\tau$

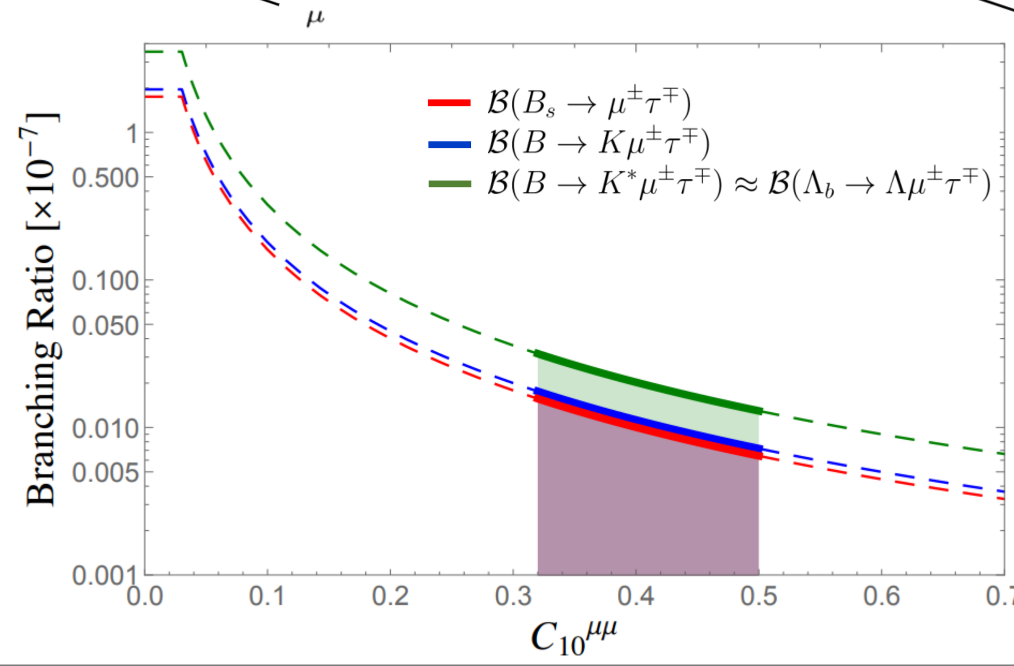


Needs data on $g_{\mu\mu}^{L(R)}$, extracted from [3]



- Results:

$$\mathcal{B}(B_s \to \mu^\pm\tau^\mp) < 1.6 \times 10^{-9}$$
$$\mathcal{B}(B \to K\mu^\pm\tau^\mp) < 1.8 \times 10^{-9}$$
$$\mathcal{B}(B \to K^*\mu^\pm\tau^\mp) < 3.3 \times 10^{-9}$$
$$\approx \mathcal{B}(\Lambda_b \to \Lambda\mu^\pm\tau^\mp)$$




## References


1. Damir Becirevic, Olcyr Sumensari, and Renata Zukanovich Funchal, *Lepton flavor violation in exclusive b → s decays*, The European Physical Journal C 76 (2016), no. 3.
2. Andrei Angelescu, Darius A. Faroughy, and Olcyr Sumensari, *Lepton flavor violation and dilepton tails at the lhc*, The European Physical Journal C 80 (2020), no. 7.
3. Andrei Angelescu, Damir Becirevic, Darius A. Faroughy, Florentin Jaffredo, and Olcyr Sumensari, *On the single leptoquark solutions to the b-physics anomalies*, 2021.