Lepton flavour violation in rare Λ_b decays

Keri Vos

In collaboration with M. Bordone and M. Rahimi [2106.05192]

Maastricht University & Nikhef

Why Lepton Universality Violation?

Bordone, Rahimi, KKV, Eur.Phys.J.C (2021) 81 [2106.05192]

- Hints of Lepton flavour Universality violation sparked many new physics models
  many many references
- Common feature: sizeable Lepton Flavor Violation (LFV)
- LFV searches in mesons and baryons are complementary!
  - Example: $\Lambda_b \to \Lambda\mu^+\mu^-$ NP analysis shows different dependencies as $B \to K\mu^+\mu^-$
  - This talk: same effect for LFV searches

New Physics contributions

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_{\rm em}}{4\pi} \sum_{i=9,10,S,P} \left(C_i^{\ell_1\ell_2}(\mu)\mathcal{O}_i^{\ell_1\ell_2}(\mu) + C_i^{\prime\ell_1\ell_2}(\mu)\mathcal{O}_i^{\prime\ell_1\ell_2}(\mu) \right),$$

$$\mathcal{O}_9^{\ell_1\ell_2} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}_1\gamma^\mu \ell_2), \qquad \mathcal{O}_{10}^{\ell_1\ell_2} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}_1\gamma^\mu\gamma^5 \ell_2),$$

$$\mathcal{O}_S^{\ell_1\ell_2} = (\bar{s}P_R b)(\bar{\ell}_1\ell_2), \qquad \mathcal{O}_P^{\ell_1\ell_2} = (\bar{s}P_R b)(\bar{\ell}_1\gamma_5\ell_2)\,,$$

$$\mathcal{O}_T^{\ell_1\ell_2} = (\bar{s}\sigma^{\mu\nu} b)(\bar{\ell}_1\sigma_{\mu\nu}\ell_2)\,, \qquad \mathcal{O}_{T5}^{\ell_1\ell_2} = (\bar{s}\sigma^{\mu\nu} b)(\bar{\ell}_1\sigma_{\mu\nu}\gamma_5\ell_2)\,,$$

- $\mathcal{O}_i^{\prime\ell_1\ell_2}$ by replacing $P_L \leftrightarrow P_R$, where $P_{L/R} = \frac{1}{2}(1 \mp \gamma_5)$.
- $\mathcal{O}_7$ cannot generate LFV contributions due to the universality of EM interactions

$$\mathcal{O}_7 = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}$$

Lepton Universality Violation in Λ_b decays

Bordone, Rahimi, KKV, Eur.Phys.J.C (2021) 81 [2106.05192]

- Full angular distribution of LFV in $\Lambda_b \to \Lambda \ell_1^- \ell_2^+$

$$\frac{1}{\Gamma^{(0)}} \frac{d\Gamma(\Lambda_b(p, s_{\Lambda_b}) \to \Lambda(k, s_\Lambda)\ell_1^-(p_1)\ell_2^+(p_2))}{d\cos\theta dq^2} = a + b\cos\theta_\ell + c\cos^2\theta_\ell\,,$$

- $\cos\theta_\ell$ helicity angle in the dilepton frame
- a, b, c provided in terms of Wilson coefficients and form factors
- Form factors available from Lattice Detmold, Meinel [1602.01399]
- Also holds for $\Lambda_b \to \Lambda^* \ell_1^- \ell_2^+$ when setting the perpendicular form factor to zero

Lepton Universality Violation in Λ_b decays

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- Focus on integrated quantities:

$$\frac{d\mathcal{B}^{\ell_1\ell_2}}{dq^2} = 2\Gamma^{(0)}\tau_{\Lambda_b}\left(a + \frac{c}{3}\right) ,$$

$$\frac{dA_{\rm FB}^{\ell_1\ell_2}}{dq^2} = \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta dq^2} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta dq^2}}{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta dq^2} + \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta dq^2}} = \frac{b}{2\left(a+\frac{c}{3}\right)} ,$$

- Neglect $\mathcal{O}_{T,T5}$ and $\mathcal{O}'$ operators because they are not appealing to explain B anomalies
- Mesonic and Baryonic modes have different dependencies
- Present easy results in the form of:

$$10^8 \cdot \mathcal{B}^{\ell_1\ell_2} = \xi_9^{\ell_1\ell_2}|C_9^{\ell_1\ell_2}|^2 + \xi_{10}^{\ell_1\ell_2}|C_{10}^{\ell_1\ell_2}|^2 + \xi_S^{\ell_1\ell_2}|C_S^{\ell_1\ell_2}|^2 + \xi_P^{\ell_1\ell_2}|C_P^{\ell_1\ell_2}|^2 + \xi_{9S}^{\ell_1\ell_2}\mathrm{Re}(C_9^{\ell_1\ell_2}C_S^{*\ell_1\ell_2}) + \xi_{10P}^{\ell_1\ell_2}\,\mathrm{Re}(C_{10}^{\ell_1\ell_2}C_P^{*\ell_1\ell_2})$$

LFV in meson decays - model independent

Bordone, Rahimi, KKV, Eur.Phys.J.C (2021) 81 [2106.05192]

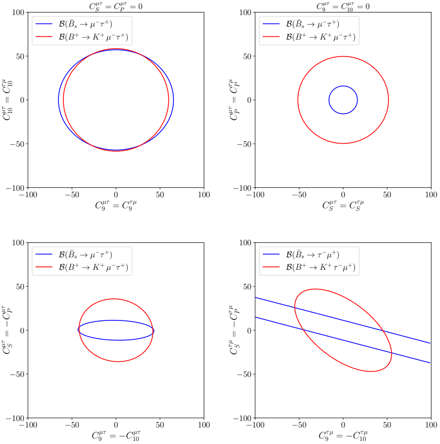
	$\ell_1 = \mu,\ \ell_2 = \tau$	$\ell_1 = \mu,\ \ell_2 = e$
$\xi_9^{\ell_1\ell_2}$	2.15 ± 0.11	3.13 ± 0.20
$\xi_{10}^{\ell_1\ell_2}$	2.08 ± 0.10	3.13 ± 0.20
$\xi_S^{\ell_1\ell_2}$	0.980 ± 0.057	1.83 ± 0.11
$\xi_P^{\ell_1\ell_2}$	1.06 ± 0.06	1.83 ± 0.11
$\xi_{9S}^{\ell_1\ell_2}$	-0.973 ± 0.059	0.142 ± 0.013
$\xi_{10P}^{\ell_1\ell_2}$	1.20 ± 0.07	0.144 ± 0.013

- For μe: $\xi_9^{\ell_1\ell_2} = \xi_{10}^{\ell_1\ell_2}$
  - only $|C_9^{\ell_1\ell_2}|^2 + |C_{10}^{\ell_1\ell_2}|^2$ and $|C_P^{\ell_1\ell_2}|^2 + |C_S^{\ell_1\ell_2}|^2$ can be constrained
- Independent of charges except $\xi_{9S}^{e\mu} = -\xi_{9S}^{\mu e}$
- Uncertainties from form factor
- Can be compared to similar coefficients for the meson case

Constraints from the Meson sector

Bordone, Rahimi, KKV, Eur.Phys.J.C (2021) 81 [2106.05192]

Model independent constraints from $B \to K\tau\mu$ and $B_s \to \mu\tau$



Combination of coefficients inspired by SMEFT

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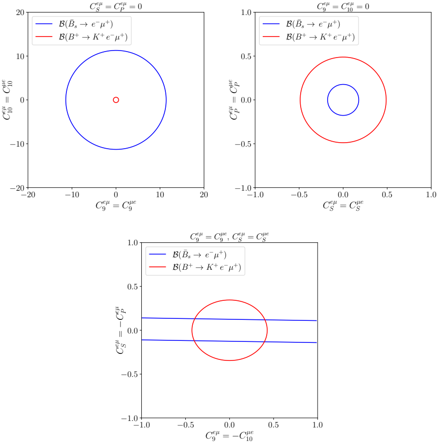

Interplay between mesonic and baryonic LFV

LFV in baryonic decays - model independent

Bordone, Rahimi, KKV, Eur.Phys.J.C (2021) 81 [2106.05192]

Current limits on mesonic modes imply upper limits on baryonic modes

	$\mathcal{B}^{\mu\tau}$ $(\mathcal{B}^{\tau\mu}) \times 10^{-5}$	$\mathcal{B}^{e\mu} = \mathcal{B}^{\mu e} \times 10^{-8}$
$C_9^{\ell_1\ell_2} \neq 0, C_{10}^{\ell_1\ell_2} \neq 0, C_S^{\ell_1\ell_2} = C_P^{\ell_1\ell_2} = 0$	< 7.7 (7.7)	< 1.1
$C_S^{\ell_1\ell_2} \neq 0, C_P^{\ell_1\ell_2} \neq 0, C_9^{\ell_1\ell_2} = C_{10}^{\ell_1\ell_2} = 0$	< 2.7 (2.7)	< 0.06
$C_9^{\ell_1\ell_2} = -C_{10}^{\ell_1\ell_2}, C_S^{\ell_1\ell_2} = -C_P^{\ell_1\ell_2}$	< 7.4 (11)	< 1.1

- Any future experimental upperlimit below the quoted will provide stronger constraints on the Wilson coefficients!
- Complementarity between Hadrons and leptons:
  - Mainly for both (axial)vector and (pseudo)scalar combinations

LFV in baryonic decays - model independent

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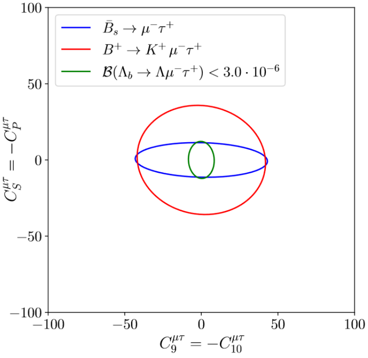
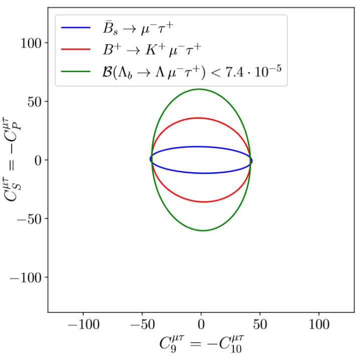
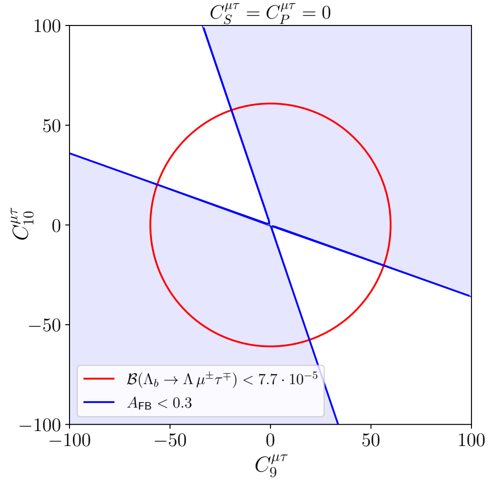
Complementarity between Hadrons and leptons!





Forward-backward asymmetry

- Complementary to branching ratio
- $A_{\mathrm{FB}} = 0$ for $C_9 = C_{10}$ and in general independent of their values



Specific NP models

Froggatt-Nielsen Mechanism

Bordone, Rahimi, KKV, Eur.Phys.J.C (2021) 81 [2106.05192]
Bordone, Cata, Feldmann, Mandal, JHEP 03 (2021) 122, [2010.03297]

- FN introduces $U(1)$ symmetry and $U(1)$ charges to each quark multiplet Froggatt, Nielsen (1979)
- Can accommodate the SM flavour hierarchies
- Flavour non-diagonal transitions suppressed by powers of λ
- Assign FN charges to SM fields Bordone, Cata, Feldmann [1910.02641]
- Generalized FN: every flavour structure in SMEFT determined by difference of FN charges
- Gives a power counting for NP operators
- Simultaneous solution for anomalies and flavour puzzle

Froggatt-Nielsen Mechanism

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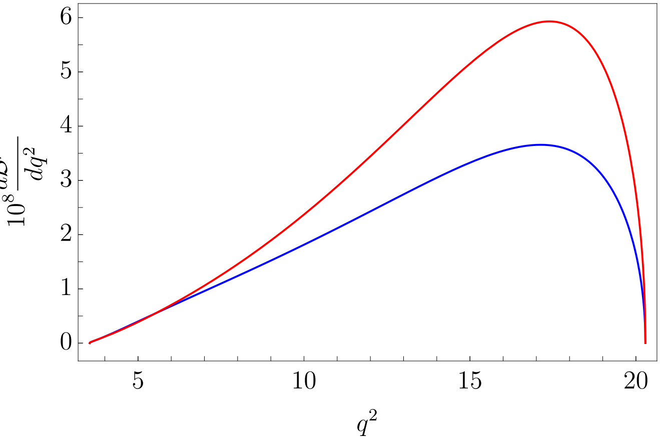
S1 + S3 scalar leptoquarks scenario

$$\mathcal{B}^{\mu\tau} = (7.1 \pm 2.5) \cdot 10^{-9} \text{ and } \mathcal{B}^{\tau\mu} = (4.2 \pm 1.7) \cdot 10^{-6}$$

Discussion

NP effect on differential rate

Plots by Marzia Bordone

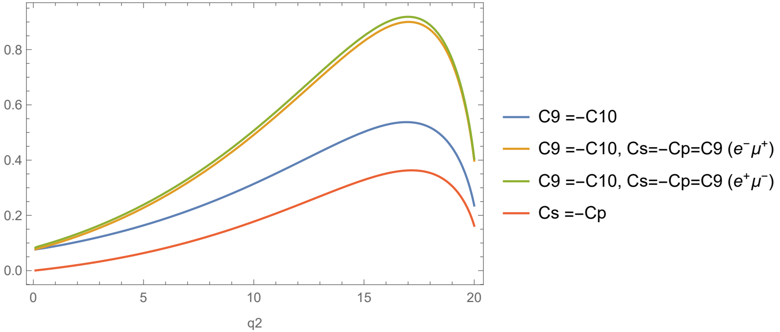


- $\tau\mu$ final state
- Blue: $C_9 = -C_{10}$
- Red: $C_9 = -C_{10}$ and $C_S = -C_P$

NP effect on differential rate

We provided a notebook for LHCb

- Differential distributions as a function of q^2 and $\cos\theta_\ell$
- Different NP scenarios: formulas divided by the Wilson coefficients



Discussion

- What can we provide to help improve the Monte Carlo?
- How to obtain the required weights?
- Is our $\cos\theta_\ell$ definition the same as LHCb? Or easy to convert?
- Which charge configurations are relevant?

Backup

NP effect on differential rate

Plots by Marzia Bordone

	$\ell_1^- = \mu^-, \ell_2^+ = \tau^+$	$\ell_1^- = \mu^-, \ell_2^+ = e^+$
$c_{\ell_1\ell_2}^{9+}$	1.09	1.75
$c_{\ell_1\ell_2}^{10+}$	1.14	1.75
$c_{\ell_1\ell_2}^{S}$	1.47	2.68
$c_{\ell_1\ell_2}^{P}$	1.58	2.68
$c_{\ell_1\ell_2}^{S9}$	-1.35	0.21
$c_{\ell_1\ell_2}^{P10}$	1.66	0.21

- Coefficients for $B \to K\ell_1\ell_2$

Details on kinematics

- In the Λ_b rest frame ($\Lambda_b - \mathrm{RF}$)

$$
\begin{aligned}
q^\mu|_{\Lambda_b-\mathrm{RF}} &= (q^0, 0, 0, -|\vec{q}|)\,, \\
k^\mu|_{\Lambda_b-\mathrm{RF}} &= (m_{\Lambda_b} - q^0, 0, 0, |\vec{q}|)\,.
\end{aligned}
$$

$$
q^0|_{\Lambda_b-\mathrm{RF}} = \frac{m_{\Lambda_b}^2 - m_\Lambda^2 + q^2}{2m_{\Lambda_b}}\,, \quad \text{and} \quad |\vec{q}||_{\Lambda_b-\mathrm{RF}} = \frac{\sqrt{\lambda(m_{\Lambda_b}^2, m_\Lambda^2, q^2)}}{2m_{\Lambda_b}}\,,
$$

- In the dilepton rest frame

$$
\begin{aligned}
p_1^\mu|_{2\ell-\mathrm{RF}} &= (E_{\ell_1}, -|\vec{p}_2||_{2\ell-\mathrm{RF}} \sin\theta_\ell, 0, -|\vec{p}_2||_{2\ell-\mathrm{RF}} \cos\theta_\ell)\,, \\
p_2^\mu|_{2\ell-\mathrm{RF}} &= (E_{\ell_2}, +|\vec{p}_2||_{2\ell-\mathrm{RF}} \sin\theta_\ell, 0, +|\vec{p}_2||_{2\ell-\mathrm{RF}} \cos\theta_\ell)\,,
\end{aligned}
$$

$$
|\vec{p}_2||_{2\ell-\mathrm{RF}} = \frac{\sqrt{\lambda(q^2, m_{\ell_1}^2, m_{\ell_2}^2)}}{2\sqrt{q^2}}\,, \quad \text{and} \quad E_{\ell_{1,2}} = \frac{q^2 + m_{\ell_{1,2}}^2 - m_{\ell_{2,1}}^2}{2\sqrt{q^2}}\,.
$$