New ideas for Rare decays

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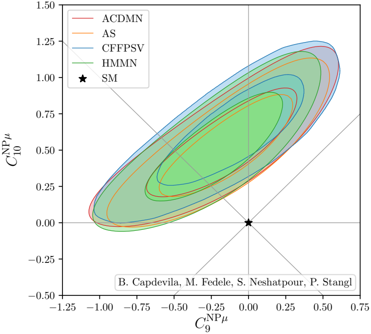
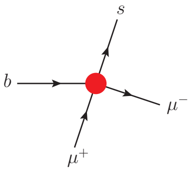
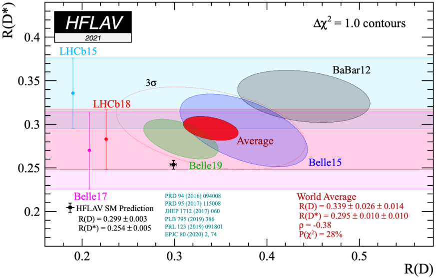


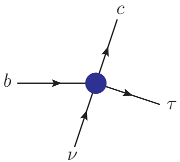
ACDMN
AS
CFFPSV
HMMN
SM
B. Capdevila, M. Fedele, S. Neshatpour, P. Stangl
$C_{10}^{\mathrm{NP}\mu}$
$C_9^{\mathrm{NP}\mu}$



b
s
μ^-
μ^+



HFLAV
2021
$\Delta\chi^2 = 1.0$ contours
LHCb15
BaBar12
3σ
LHCb18
Average
Belle15
Belle19
Belle17
HFLAV SM Prediction
R(D) = 0.299 ± 0.003
R(D*) = 0.254 ± 0.005
PRD 94 (2016) 094008
PRD 95 (2017) 115008
JHEP 1712 (2017) 060
PLB 795 (2019) 386
PRL 123 (2019) 091801
EPJC 80 (2020) 2, 74
World Average
R(D) = 0.339 ± 0.026 ± 0.014
R(D*) = 0.295 ± 0.010 ± 0.010
ρ = -0.38
P(χ²) = 28%
R(D*)
R(D)



b
c
τ
ν

What New Physics?

- The NP effective scale for FCNC:

$$\frac{g_{\rm RD}^2}{\Lambda^2} \sim \frac{1}{(40\,{\rm TeV})^2}$$

$\Rightarrow$ $\sim 20\%$ deviation competes with loop suppression in the SM

- The NP effective scale for FCNC:

$$\frac{g_{\rm CC}^2}{\Lambda^2} \sim \frac{1}{(3\,{\rm TeV})^2}$$

$\Rightarrow$ $\sim 15\%$ deviation competes with tree-level process in the SM

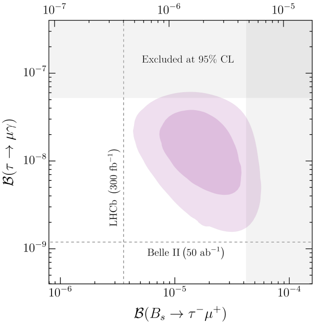
- Implies $g_{\rm CC} \gg g_{\rm RD}$

What's allowed?

$$\mathcal{L}_{\mathrm{EFT}}^{\mathrm{NP}} = \left[\mathcal{C}_T^{ij\alpha\beta} (\bar{q}_L^i \gamma_\mu T^a q_L^j)(\bar{\ell}_L^\alpha \gamma^\mu T^a \ell_L^\beta) + \mathcal{C}_S^{ij\alpha\beta} (\bar{q}_L^i \gamma_\mu q_L^j)(\bar{\ell}_L^\alpha \gamma^\mu \ell_L^\beta) \right]$$

complex tensors in flavour space

- The flavour structure of the Wilson coefficients is complex
- In particular for leptoquark scenarios, LFV decays are generated



[Cornella et al, '21]

- LFV is the smoking gun of a large class of processes

  ⇒ Current experimental limits are challenging the allowed parameter space

- Possible exception by gauging flavour

  [see Admir's talk]

How do we corroborate the anomalies?

NP is expected to have a rich phenomenology and we have to assess its flavour structure:

- Using the $b \to d$ transition

  $\Rightarrow$ test the $3 \to 1$ flavour couplings

- Studying other hadronic decay channels

  $\Rightarrow$ baryon decays provide complementary/orthogonal information due to their different flavour spin structure

Two examples:

- LFU with $B^+ \to \pi^+ \ell^+ \ell^-$
- LFV with $\Lambda_b \to \Lambda \ell_1^+ \ell_2^-$

LFU in $B \to \pi$

$B \to \pi \ell^+ \ell^-$

- $B^+ \to \pi^+ \ell^+ \ell^-$ is a very rare decay

$$\frac{\mathcal{B}(B^+ \to \pi^+ \ell^+ \ell^-)}{\mathcal{B}(B^+ \to K^+ \ell^+ \ell^-)} = \frac{|V_{td}|^2}{|V_{ts}|^2} = 10^{-2}$$

$\Rightarrow$ Observed at LHCb **[1509.00414]**

- Difference in CKM scaling

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} \left[V_{ub} V_{ud}^* (C_1 \mathcal{O}_{1u} + C_2 \mathcal{O}_{2u}) + V_{cb} V_{cd}^* (C_1 \mathcal{O}_{1c} + C_2 \mathcal{O}_{2c}) - V_{tb} V_{td}^* \sum_{i>3} C_i \mathcal{O}_i \right]$$

$\Rightarrow$ Light mass resonances are not CKM suppressed

$\Rightarrow$ Their impact on observables has to be estimated

$B \to \pi \ell^+ \ell^-$

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$\uparrow$ λ^3 $\quad$ $\uparrow$ λ^3 $\quad$ $\uparrow$ λ^3

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Long distance effects

$$\mathcal{C}_9^\ell \to \mathcal{C}_9^{\ell,\text{eff}}(q^2) \equiv \mathcal{C}_9^\ell - \frac{V_{cd}^* V_{cb}}{V_{td}^* V_{tb}} Y_{c\bar{c}}(q^2) + Y_{\text{light}}(q^2)$$

- We parametrise the Y functions through dispersion relations, using leading single-particle intermediate state

$$Y_{q\bar{q}}^{\text{1P}} \sim \sum_{V_j} \eta_j e^{i\delta_j} \frac{(q^2 - q_0^2)}{(m_j^2 - q_0^2)} \frac{m_j \Gamma_j}{m_j^2 - q^2 - i m_j \Gamma_j}$$

  $\Rightarrow$ $q_0^2 = 0$ for the charm

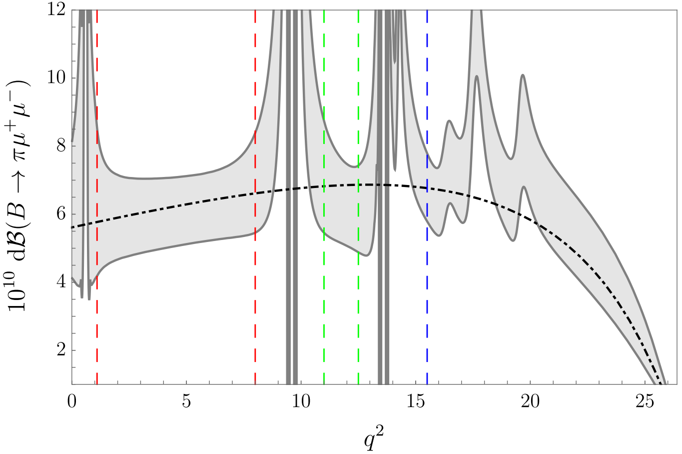
  $\Rightarrow$ unsubtracted for light-quark resonances

- η_V and δ_V are not known a priori

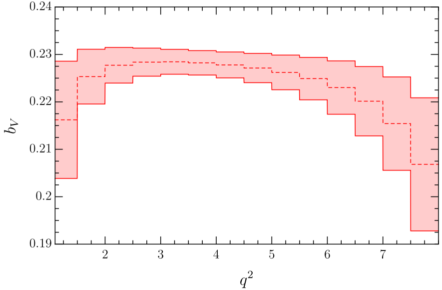
  $\Rightarrow$ η_V can be extracted from $\mathcal{B}(B \to \pi V_j) \times \mathcal{B}(V_j \to \ell^+\ell^-)$

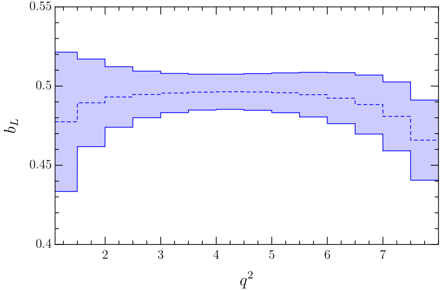
  $\Rightarrow$ δ_V is extracted from $B \to K\ell^+\ell^-$ for the charm

  $\Rightarrow$ δ_V is varied randomly for light-quark resonances



- The band includes uncertainties from the form factors and the resonances parameters





$$R_\pi[q^2_{\rm min}, q^2_{\rm max}] = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(B\to\pi\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(B\to\pi e^+e^-)}{dq^2} dq^2}$$
$$= R_\pi^{\rm SM} + b_V \Delta\mathcal{C}_9$$
$$+ (b_V - b_L)\Delta\mathcal{C}_{10}$$

- b_V controls vector interactions
- b_L controls left-handed interactions

If NP is the same that in $b \to s\ell\ell$:

$$R_\pi|^{\rm NP} = 0.79 \pm 0.05_{\rm NP} \pm 0.02_{\rm LD}\,,$$

$\Rightarrow$ $q^2 \in [1.1, 6]\,{\rm GeV}^2$: $\sim 3\sigma$ at $300\,{\rm fb}^{-1}$

$\Rightarrow$ $q^2 \in [1.1, 8]\,{\rm GeV}^2$: $\sim 3\sigma$ at $50\,{\rm fb}^{-1}$

LFV in baryon decays

$\Lambda_b \to \Lambda \ell_1^+ \ell_2^-$

- The matrix elements of $\Lambda_b \to \Lambda$ are characterized by a large number of independent structures (10 FFs)

- Complete set of LFV NP operators:

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

$$\begin{aligned} \mathcal{O}_9^{(\prime)\ell_1\ell_2} &= (\bar{s}\gamma_\mu P_L b)(\bar{\ell}_1 \gamma^\mu \ell_2), & \mathcal{O}_{10}^{(\prime)\ell_1\ell_2} &= (\bar{s}\gamma_\mu P_L b)(\bar{\ell}_1 \gamma^\mu \gamma^5 \ell_2), \\ \mathcal{O}_S^{(\prime)\ell_1\ell_2} &= (\bar{s} P_R b)(\bar{\ell}_1 \ell_2), & \mathcal{O}_P^{(\prime)\ell_1\ell_2} &= (\bar{s} P_R b)(\bar{\ell}_1 \gamma_5 \ell_2), \\ \mathcal{O}_T^{\ell_1\ell_2} &= (\bar{s}\sigma^{\mu\nu} b)(\bar{\ell}_1 \sigma_{\mu\nu} \ell_2), & \mathcal{O}_{T5}^{\ell_1\ell_2} &= (\bar{s}\sigma^{\mu\nu} b)(\bar{\ell}_1 \sigma_{\mu\nu} \gamma_5 \ell_2), \end{aligned}$$

$\Rightarrow$ Can we extract more information from LFV baryon decays?

[MB, Rahimi, Vos, '21]

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

$$A_{\mathrm{FB}}^{\ell_1\ell_2} = \Big[\rho^{\ell_1\ell_2}(|C_{10}^{\ell_1\ell_2}|^2 + |C_9^{\ell_1\ell_2}|^2) + \rho_{910}^{\ell_1\ell_2}\mathrm{Re}(C_9^{\ell_1\ell_2}C_{10}^{*\ell_1\ell_2}) + \rho_{9S}^{\ell_1\ell_2}\mathrm{Re}(C_9^{\ell_1\ell_2}C_S^{*\ell_1\ell_2}) + \rho_{10P}^{\ell_1\ell_2}\mathrm{Re}(C_{10}^{\ell_1\ell_2}C_P^{*\ell_1\ell_2})\Big]\Big/\Gamma^{\ell_1\ell_2},$$

	$\ell_1 = \mu,\, \ell_2 = \tau$	$\ell_1 = \mu,\, \ell_2 = e$
$\xi_9^{\ell_1\ell_2}$	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

- Form factors from Lattice QCD [W.Detmold, S.Meinel, '16]
- Coefficients of the same order of the ones for $B \to K\ell_1\ell_2$
- Substantial difference in relative size of interference terms
- Similar table for $\rho_i^{\ell_1\ell_2}$

[MB, Rahimi, Vos, '21]

usable for MC study at LHCb

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

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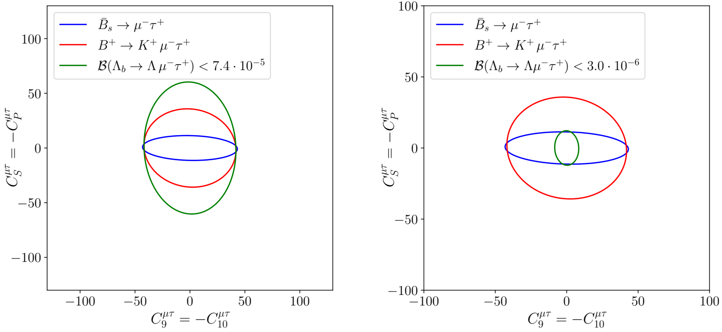

- Complementarity of baryon and meson LFV decay is highly dependent on the NP scenario

- $\Lambda_b \to \Lambda\mu^-\tau^+$ can put more stringent constraints on $C_{9(10)}^{\mu\tau}$

Prospects at LHCb

[MB, Rahimi, Vos, '21]

$$\frac{\mathcal{N}(\Lambda_b \to \Lambda(\to p\pi)\ell_1\ell_2)}{\mathcal{N}(B^+ \to K^+\ell_1\ell_2)} = \frac{\mathcal{B}(\Lambda_b \to \Lambda(\to p\pi)\ell_1\ell_2)|_{\text{theory}}}{\mathcal{B}(B^+ \to K^+\ell_1\ell_2)|_{\text{theory}}} \frac{f_{\Lambda_b}}{f_{B^+}} r_{\Lambda_b/B^+}$$

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fragmentation fractions

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ratio of reconstruction efficiencies

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ratio of reconstruction efficiencies

- From LHCb mesurement:

$$\frac{f_{\Lambda_b}}{f_{B^+}} = 0.518 \pm 0.036$$

  assuming $f_{B^+} = (f_u + f_d)/2$

- $\mathcal{B}(\Lambda_b \to \Lambda(\to p\pi)\ell_1\ell_2)|_{\text{theory}} \sim \mathcal{B}(B^+ \to K^+\ell_1\ell_2)|_{\text{theory}}$

- We estimate $r_{\Lambda_b/B^+} \sim 1.67$ from the ratio $\mathcal{N}(\Lambda_b \to \Lambda(\to p\pi)\mu^-\mu^+)/\mathcal{N}(B^+ \to K^+\mu^-\mu^+)$

Prospects at LHCb

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fragmentation fractions ($\frac{f_{\Lambda_b}}{f_{B^+}}$)

ratio of reconstruction efficiencies (r_{Λ_b/B^+})

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$$\boxed{\mathcal{B}(\Lambda_b \to \Lambda(\to p\pi)\mu^-\tau^+) \lesssim 6.5 \cdot 10^{-5}}$$

Summary

- Rare decays are interesting probes of physics within and beyond the Standard Model
- New Physics scenarios inspired by B anomalies have to be corroborated by further measurements
- To understand the full flavour structure of New Physics coupling, $b \to d\ell\ell$ decays have to be studied
    - R_π is an interesting probe of this transition
- Heavy baryon decays allow to set complementary/orthogonal constraints
    - LFV Λ_b decays are accessible at LHCb and provide a further test of NP scenarios