LFV in meson and baryon decays
– TH overview –

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Overview

- *Short overview of $b \to s$ and $b \to c$ data*
- *LFV in B decays: general arguments*
- *LFV in Kaon decays?*
- *Status of searches*

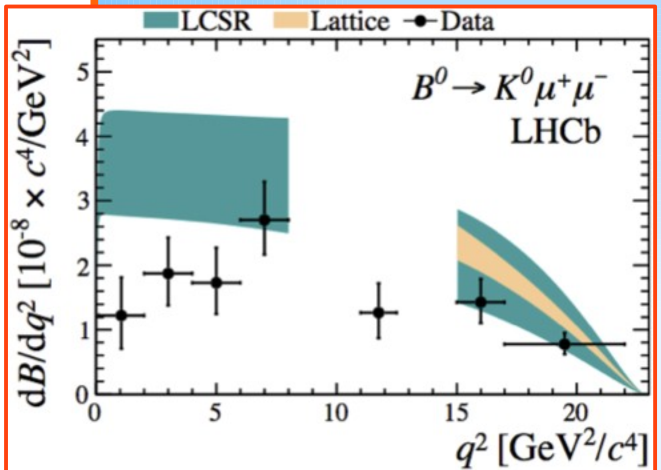
Collider Data

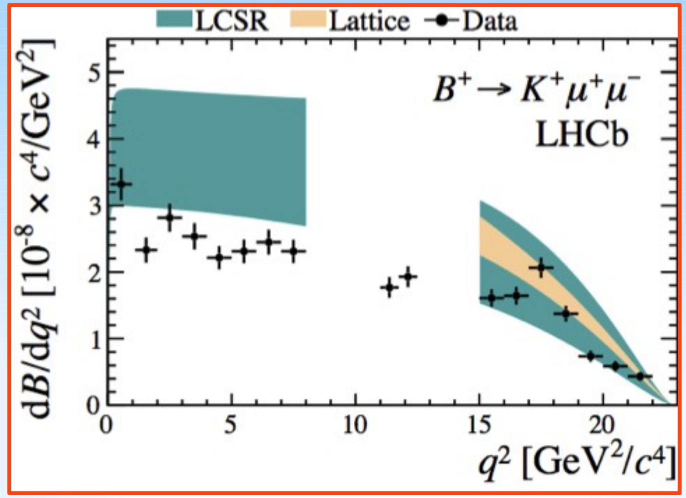
- *No direct evidence of BSM at colliders*
- *A coherent set of discrepancies in B decays*

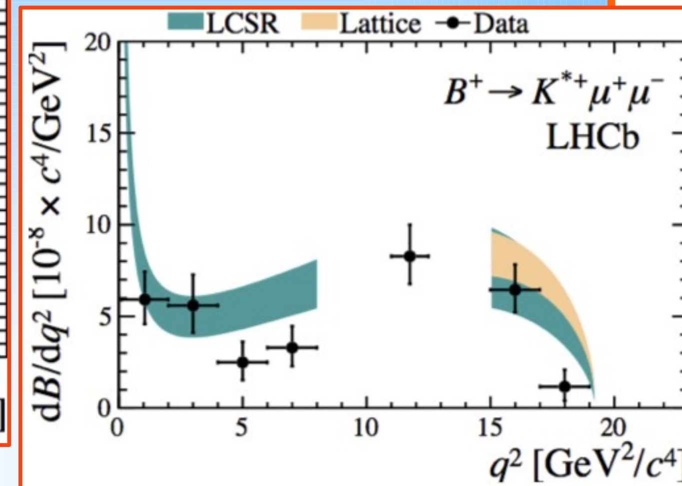
❶ $b \to s\, \mu\mu$ *BR data < SM*

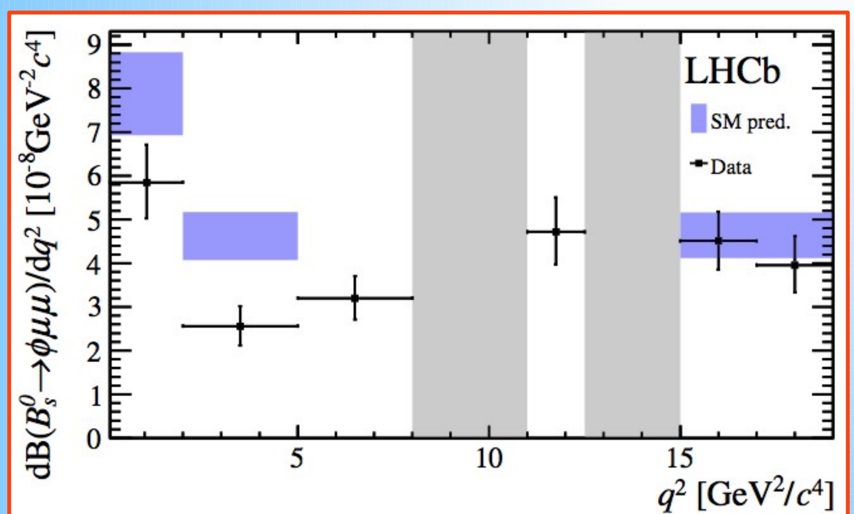
Challenge: B → light meson f.f.'s

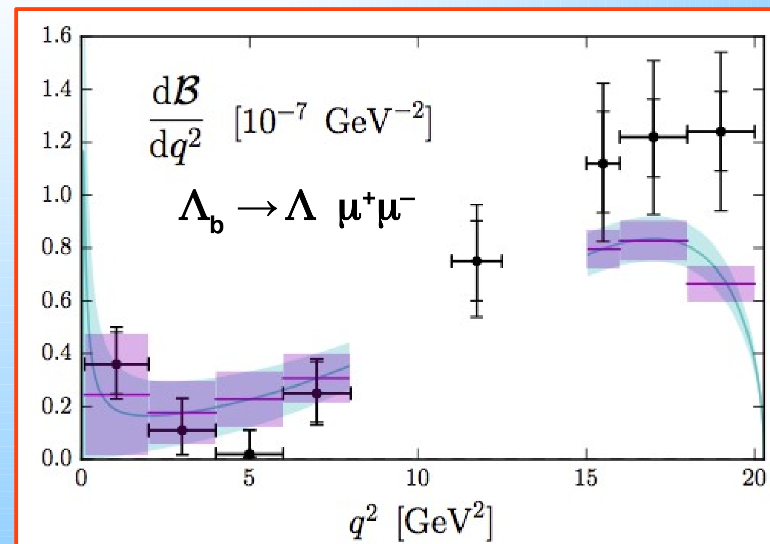
$b \to s\,\mu\mu$ BR data < SM











Collider Data

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1. $b \to s\,\mu\mu$ *BR data < SM*
   Challenge: $B \to$ light meson f.f.'s
2. $B \to K^*\,\mu\mu$ *angular data*
   Challenge: charm loops
3. $b \to s\,\mu\mu \;/\; b \to s\,ee$ *ratios*
   Challenge: (mostly) stats

loop processes (1–3)

4. $b \to c\,\tau\nu \;/\; b \to c\,\ell\nu$ *ratios*
   Challenge: stats + syst

tree processes (4)

Minimal TH considerations

(before any fit)

EFT considerations

❶ *Quite remarkably, most data hint at shifts to just 2 eff. couplings*

$$H(\bar{b} \to \bar{s}\mu\mu) = -\frac{4 G_F}{\sqrt{2}} V_{tb}^* V_{ts} \frac{\alpha_{\rm em}}{4\pi} \left[\bar{b}_L \gamma^\lambda s_L \cdot \left(\boxed{C_9^{(\mu)}} \bar{\mu} \gamma_\lambda \mu + \boxed{C_{10}^{(\mu)}} \bar{\mu} \gamma_\lambda \gamma_5 \mu \right) \right]$$

$+$ RH-quark ops. $+$ dipoles

$+$ scalar & tensor ops.

Effects are (mostly) here

❷ *Also remarkably, two scenarios stand out:*

$dC_9^{(\mu)}$ *alone*

$$\boxed{dC_9^{(\mu)} = -dC_{10}^{(\mu)}}$$ [Hiller-Schmaltz, 2014]

this op. combination can be written in terms of $SU(2)_L$ invariants

[Alonso, Grinstein, M.Camalich, 2014]

⇨ *well-suited to UV-complete models*

EFT considerations

❷ *More on* $dC_9^{(\mu)}$ *vs.* $dC_9^{(\mu)} = -dC_{10}^{(\mu)}$

How to resolve between the two scenarios?

⇨ *Accurate* $B_s \to \mu\mu$ *measurement*

- *present single-measurement error* $\simeq$ *20 %*

- *exp combi may soon be able to confirm or exclude deviations of* C_{10} *of O(10%)*

More TH considerations

❸ *Pattern of Lepton Universality Violation in* $b \to s$

The observed new-physics hierarchy:

effects in ee $\ll$ *effects in* $\mu\mu$ $\ll$ *(allowed) effects in* $\tau\tau$

suggestive of NP coupled dominantly to 3rd *gen. SM fermions*

[Glashow *et al., 2015*]

❹ *… which in turn makes it natural to link* $b \to s$ *and* $b \to c$ *data*

[Bhattacharya *et al., 2015*]

Data now allow to disprove some, and to make more precise some other of these considerations

1-Wilson-coeff. picture

[Carvunis *et al.*, *2102.13390*]

		Pre-Moriond 2021			Post-Moriond 2021		
Scenario		Best-fit	Pull	p-value	Best-fit	Pull	p-value
C_7	$\mathbb{R}$	-0.0079	0.58σ	0.11%	-0.0079	0.57σ	0.12%
	$\mathbb{C}$	$-0.0045-0.056\,i$	0.61σ	0.11%	$-0.0044-0.056\,i$	0.61σ	0.11%
C_9	$\mathbb{R}$	-0.97	$\mathbf{6.4\sigma}$	10.0%	-0.93	$\mathbf{6.7\sigma}$	12.0%
	$\mathbb{C}$	$-0.98-0.22\,i$	$\mathbf{6.1\sigma}$	9.4%	$-0.93-0.25\,i$	$\mathbf{6.4\sigma}$	12.0%
C_{10}	$\mathbb{R}$	0.72	$\mathbf{5.8\sigma}$	6.1%	0.68	$\mathbf{6.0\sigma}$	5.7%
	$\mathbb{C}$	$0.80+0.74\,i$	$\mathbf{5.6\sigma}$	6.0%	$0.76+0.75\,i$	$\mathbf{5.8\sigma}$	5.6%
C_{LL}	$\mathbb{R}$	-1.1	$\mathbf{6.9\sigma}$	18.0%	-0.96	$\mathbf{7.0\sigma}$	16.0%
	$\mathbb{C}$	$-1.2-1.5\,i$	$\mathbf{6.7\sigma}$	18.0%	$-1.1-1.4\,i$	$\mathbf{6.8\sigma}$	16.0%

[See Altmannshofer-Stangl, 2103.13370, for a comprehensive discussion including CPV]

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- *Two scenarios stand out: C_9 alone or $C_9 = - C_{10}$ (μμ-channel only)*
- *C_{10} alone also ok, but angular $B \to K^* \mu\mu$ anomaly unresolved*

Why LFV

If we observe LUV, then, in general
we should expect observable LFV as well

Exceptions require that the specific LUV dynamics
has some ad hoc symmetry that prevents LFV

Model zero

- *All $b \to s$ data are explained at one stroke if one assumes*
  - $(V-A)_q \times (V-A)_\ell$ *structure*
  - *with Wilson-coeff. shift much larger for $\mu\mu$ than for ee*

- *Such pattern can be obtained from a purely 3rd-generation interaction of the kind* [Glashow *et al.*, 1411.0565]

$$H_{\mathrm{NP}} = G\,(\bar{b}'_L \gamma^\lambda b'_L)\,(\bar{\tau}'_L \gamma_\lambda \tau'_L)$$

with $G = 1/\Lambda^2_{\mathrm{NP}} \ll G_F$

Model zero

- ***Note:*** *primed fields in* $H_{\rm NP} = G\,(\bar{b}'_L \gamma^\lambda b'_L)\,(\bar{\tau}'_L \gamma_\lambda \tau'_L)$
  - *Above the EWSB scale, fields are in the "gauge" basis, not the mass eigenbasis*
  - *Mass-basis unitary transformations induces LUV and LFV effects*

mass basis

$$b'_L \equiv (d'_L)_3 = (U^d_L)_{3i}\,\boxed{(d_L)_i}$$

$$\tau'_L \equiv (\ell'_L)_3 = (U^\ell_L)_{3i}\,\boxed{(\ell_L)_i}$$

- *One can then parametrically relate measured LUV ($R_{K(*)}$) to LFV decays such as B → (K) τμ*

$$BR(B^+ \to K^+ \ell_1^\pm \ell_2^\mp) \simeq \underbrace{\boxed{2\frac{(\sqrt{R_K}-1)^2}{R_K}}}_{= 2\%} \cdot \text{func.}(U^\ell_L \text{ ratios}) \cdot \underbrace{\boxed{BR(B^+ \to K^+ \mu\mu)}}_{= 4\times 10^{-7}}$$

⇨ *BRs ~ 10^{-8} expected, for generic choices of U matrices*

Model zero

- ***Note:*** *primed fields in* $H_{\rm NP} = G\left(\bar{b}'_L \gamma^\lambda b'_L\right)\left(\bar{\tau}'_L \gamma_\lambda \tau'_L\right)$
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⇨ *BRs ~ 10^{-8} expected, for generic choices of U matrices*

Lepton-decay LFV

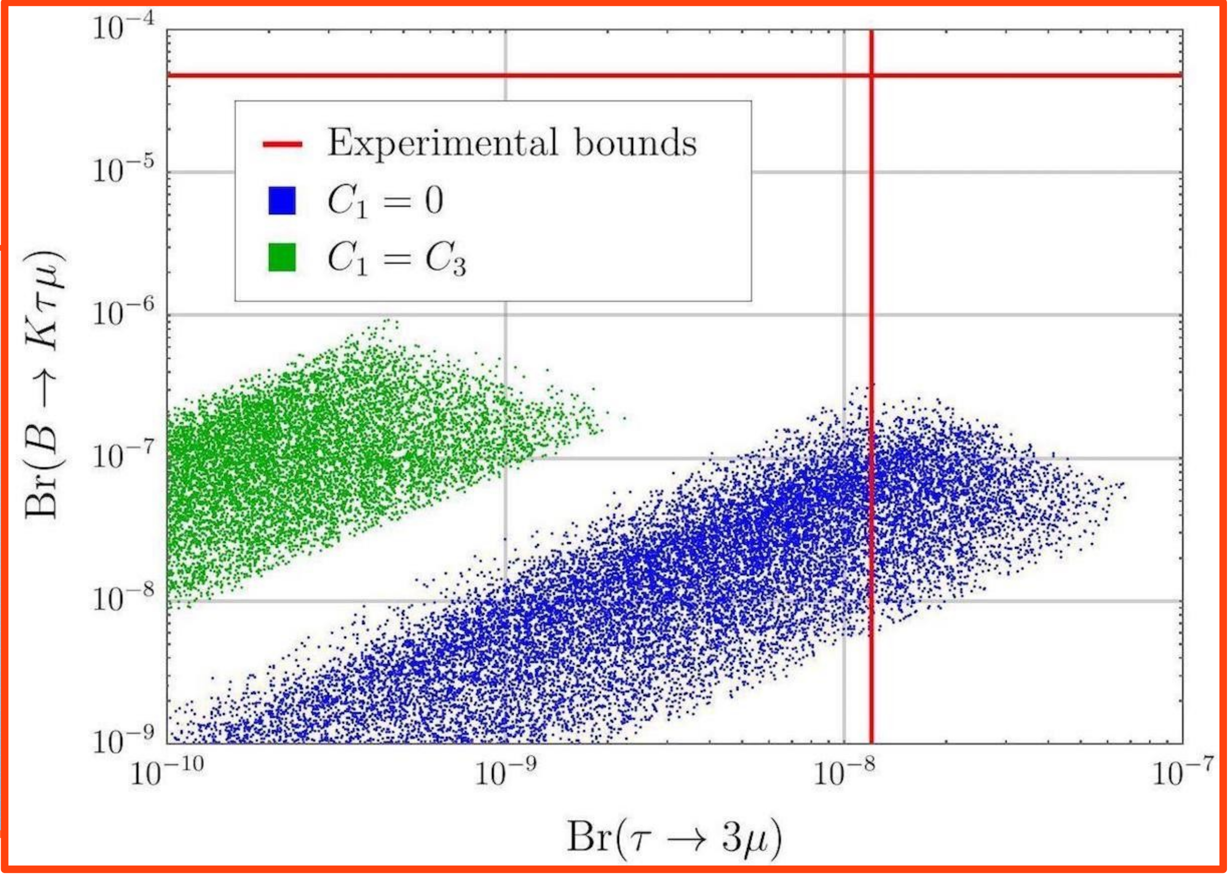
[Feruglio, Paradisi, Pattori, '16, '17]

- *Actually certain LFV decays represent strong constraints*

- *Given, at the UV matching scale*

$$\mathcal{L}^0_{NP}(\Lambda) = \frac{1}{\Lambda^2}\left(C_1\ \bar{q}'_{3L}\gamma^\mu q'_{3L}\ \bar{\ell}'_{3L}\gamma_\mu \ell'_{3L} + C_3\ \bar{q}'_{3L}\gamma^\mu \tau^a q'_{3L}\ \bar{\ell}'_{3L}\gamma_\mu \tau^a \ell'_{3L}\right)$$

close the quark loop
& attach a gauge boson
→ two further leptons



LFV in explicit UV-complete models

- *Explicit UV-complete constructions (ex. the U1 vector leptoquark) generally predict B-decay LFV while fulfilling leptonic-LFV limits*

- *Example:*
  models based on the so-called (Pati-Salam)^3

- *General prediction: large $\tau \to \mu$ effective coupling due to assumed U(2)^5 flavor symmetry and its breaking pattern*

  [Bordone, Cornella, Fuentes-M, Isidori, *'18*]

$$\mathcal{B}(B_s \to \tau^+\mu^-) \approx 2\times 10^{-4}\left(\frac{\Delta R_K}{0.3}\right)^2\left(\frac{0.1}{s_\tau}\right)^2,$$

$$\mathcal{B}(B \to K^*\tau^+\mu^-) \approx 1.5\times 10^{-6}\left(\frac{\Delta R_K}{0.3}\right)^2\left(\frac{0.1}{s_\tau}\right)^2,$$

$$\mathcal{B}(B^+ \to K^+\tau^+\mu^-) \approx 2\times 10^{-5}\left(\frac{\Delta R_K}{0.3}\right)^2\left(\frac{0.1}{s_\tau}\right)^2,$$

to compare e.g. with

BR($B^+ \to K^+ \mu^- \tau^+$) < 3.9×10^{-5}

[LHCb, *2003.04352*]

LFV

in Kaon decays?

Main point

- *The putative new dynamics in B decays may yield correlated effects in suitable K decays.*

- *Especially interesting examples include*

$$K \to \pi \nu \bar{\nu} \qquad\qquad K \to (\pi) \mu e$$

- *It turns out that B-physics machines can offer complementary info on these decays w.r.t. Kaon machines, because of*
  - *the large amounts of Kaons produced*
  - *the excellent decay-reconstruction capabilities (e.g. for K_S)*

Why correlated effects

- *The new physics for B decays can usually be described by*

$$\mathcal{L}_{\text{eff}} \supset \frac{C^{(a)}_{ijkl}}{\Lambda^2}\, \mathcal{O}^{(a)}_{ijkl}$$

two-quark { i, j }
two-lepton { k, l }
operators

- *New scale Λ may be fixed by size of observed discrepancies (typically Λ = few to 10 x few TeV)* [Di Luzio, Nardecchia, *1706.01868*]

- *The C couplings encode flavor structure. If dynamics tree-level:*

$C_{ijkl} \sim \lambda^{(q)}_{ij}\, \lambda^{(\ell)}_{kl}$ *for new colorless massive bosons*

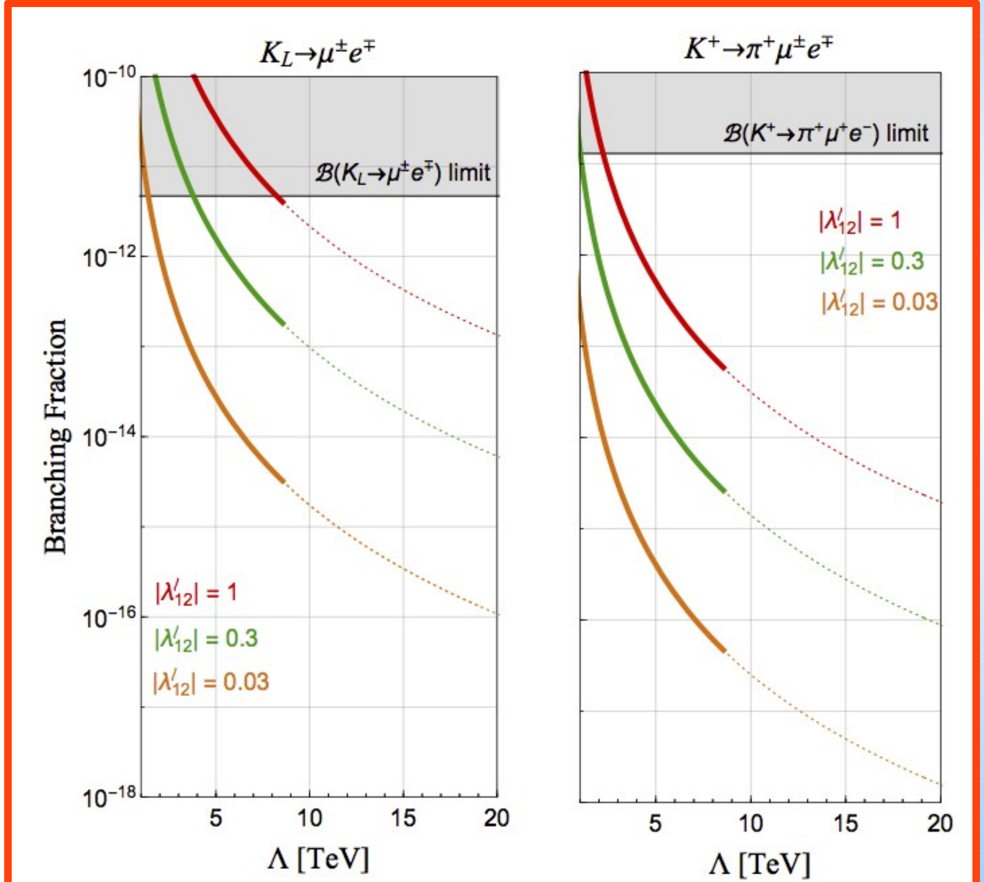
$C_{ijkl} \sim \lambda^{(q\ell)}_{il}\, (\lambda^{(q\ell)}_{jk})^*$ *for leptoquarks*

In many motivated scenarios, the λ's entering B decays and those entering K decays are highly correlated

Example

- *LHCb may well improve existing limits on* $K_L \to \mu e$ *and* $K^+ \to \pi^+ \mu e$

[Borsato *et al.*, *1808.02006*][Alves Jr. *et al.*, *1808.03477*]



TH assumptions

- *(V–A)* $\times$ *(V–A), SU(2)$_L$-invariant* $qq\ell\ell$ Hamiltonian adopted in [Buttazzo *et al.*, *1706.07808*] to explain *B* anomalies

- *CKM-like ansatz for the* $\lambda^{(q)}$ *coupling*

- *Agnostic on the* $\lambda^{(\ell)}$ *coupling*

Status

of LFV searches

Main points

- *Since the connection "measured LUV $\Leftrightarrow$ measurable LFV" was pointed out, many exp searches have been performed*

  see e.g. [P. de Simone, EPJ WoC 2020]

- *All modes involve two leptons w/ different flavours*

  Muons are the easiest $\Rightarrow$ *Best searches:* μe *and* $\mu\tau$

- *Sensitivity relies on background control:*
  - *combinatorial; semi-lept. or resonant ($c\bar{c}$) with mis-ID;*

- *Challenges to "close the kinematics"*
  - *electrons radiate*
  - *taus decay, involving missing energy*

Many recent stringent searches

$B^+ \to K^+ \mu^\pm e^\mp$ at LHCb, 7/8 TeV, 3/fb

$\mathcal{B}(B^+ \to K^+ \mu^- e^+) < 7.0\ (9.5) \times 10^{-9}$ $\mathcal{B}(B^+ \to K^+ \mu^+ e^-) < 6.4\ (8.8) \times 10^{-9}$

$\mathcal{B}(B^+ \to K^+ \mu^- \tau^+) < 3.9 \times 10^{-5}$ at LHCb, 7/8/13 TeV, 9/fb

$B^0_{(s)} \to e^\pm \mu^\mp$ at LHCb, 7/8 TeV, 3/fb

$\mathcal{B}(B^0_s \to e^\pm \mu^\mp) < 5.4\ (6.3) \times 10^{-9}$ $\mathcal{B}(B^0 \to e^\pm \mu^\mp) < 1.0\ (1.3) \times 10^{-9}$

$B^0_{(s)} \to \tau^\pm \mu^\mp$ at LHCb, 7/8 TeV, 3/fb

$\mathcal{B}\left(B^0_s \to \tau^\pm \mu^\mp\right) < 4.2 \times 10^{-5}$ $\mathcal{B}\left(B^0 \to \tau^\pm \mu^\mp\right) < 1.4 \times 10^{-5}$

Notes: *some limits are 90%, some other 95% CL; previous limits are from BaBar*

Conclusions

- *As of Moriond 2021, B anomalies hold their ground*
  One clear hint: beyond-SM LUV

- *LUV and LFV are two sides of the same broken symmetry*
  i.e. to prevent LFV requires an additional ad hoc assumption
  ⮡ *Generally, models explaining the B anomalies also predict LFV*

- *By general arguments, from the measured LUV one can expect*
  LFV BRs ~ 10^{-8} (e.g. in $B \to K \tau\mu$)

- *Using EFT-driven arguments,*
  K physics offers potential complementary probes