Lepton Flavor Violation in Exclusive $b \to s$ Decays

Olcyr Sumensari

In collaboration with D. Becirevic, R. Zukanovich Funchal and N. Kosnik

[1]LPT - Orsay

[2]Universidade de São Paulo

Rare B Decays: Theory and Experiment - Barcelona, April 20, 2016.

Outline

1. Introduction
2. LFU violation in $b \to s\ell^+\ell^-$
3. LFV in $b \to s\ell_1\ell_2$
4. Brief discussion of $h \to \mu\tau$
5. Conclusions and Perspectives

Outline

Introduction

- Lepton Flavor Universality **(LFU)** is not a fundamental symmetry of the SM: accidental in the gauge sector and broken by Yukawas.

- LFU tested in pion and kaon decays – agrees very well with the SM
$\Rightarrow$ *To be improved by NA62.*

- Renewed interest in LFUV motivated by the recently found *conflict between theory and experiment* in

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}, \quad \text{and} \quad R_K = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)}\Bigg|_{q^2\in(1,6)\ \mathrm{GeV}^2}$$

$R_{D^*}^{\mathrm{exp}} = 0.323 \pm 0.021$	$R_{D^*}^{\mathrm{th}} = 0.252 \pm 0.003^{**}$	$[3.9\sigma]^{**}$
$R_{D}^{\mathrm{exp}} = 0.41 \pm 0.05$	$R_{D}^{\mathrm{th}} = 0.31 \pm 0.02^{*}$	$[2\sigma]^{*}$
$R_{K}^{\mathrm{exp}} = 0.745^{+0.090}_{-0.074} \pm 0.036$	$R_{K}^{\mathrm{th}} = 1.003 \pm 0.001$	$[2.6\sigma]$

Introduction

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}, \qquad R_K = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)}\Bigg|_{q^2\in(1,6)\,\mathrm{GeV}^2}$$

$R_{D^*}^{\mathrm{exp}} = 0.323 \pm 0.021$	$R_{D^*}^{\mathrm{th}} = 0.252 \pm 0.003^{**}$	$[3.8\sigma]^{**}$
$R_{D}^{\mathrm{exp}} = 0.41 \pm 0.05$	$R_{D}^{\mathrm{th}} = 0.31 \pm 0.02^{*}$	$[2\sigma]^{*}$
$R_{K}^{\mathrm{exp}} = 0.745^{+0.090}_{-0.074} \pm 0.036$	$R_{K}^{\mathrm{th}} = 1.003 \pm 0.001$	$[2.6\sigma]$

- Is there a **model of NP** to explain these anomalies?
- What additional **experimental signatures** should we expect?

In general, $R_K \neq 1 \Leftrightarrow$ **LFUV** $\Rightarrow$ Lepton Flavor Violation **(LFV)**.

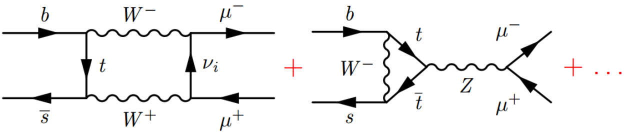
[Glashow et al, 2014.]

Outline

LFU violation

(i) $b \to s\mu^+\mu^-$

- FCNC process:



- Form-factors cancel out in the ratio $\Rightarrow$ **Extremely clean prediction**.

$$R_K \equiv \left.\frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)}\right|_{q^2\in(1,6)\,\mathrm{GeV}^2} \stackrel{\mathrm{SM}}{=} 1.003(1)$$

[Hiller, Kruger 2003]

- 2.6σ deviation observed by LHCb:

$$R_K^{\mathrm{exp}} = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{syst})$$

LFU violation

(i) $b \to s\mu^+\mu^-$

- 2.6σ deviation observed by LHCb:

$$R_K^{\text{exp}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$
$$R_K^{\text{SM}} = 1.003 \pm 0.001$$

- Instead, $\mathcal{B}(B^+ \to K^+ ee)_{q^2\in[1,6]}$ agrees with the SM, whereas

$$\mathcal{B}(B^+ \to K^+\mu\mu)^{\text{exp}}_{q^2\in[1,6]\,\text{GeV}^2} = (1.19 \pm 0.07) \times 10^{-7}$$
$$\mathcal{B}(B^+ \to K^+\mu\mu)^{\text{SM}}_{q^2\in[1,6]\,\text{GeV}^2} = (1.75^{+0.60}_{-0.29}) \times 10^{-7}$$

- $\mathcal{B}(B_s \to \mu^+\mu^-)$ is slightly smaller than the SM:

$$\overline{\mathcal{B}}(B_s \to \mu\mu)^{\text{LHCb+CMS}} = (2.8^{+0.7}_{-0.6}) \times 10^{-9} \quad \overline{\mathcal{B}}(B_s \to \mu\mu)^{\text{Atlas}} = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$$
$$\overline{\mathcal{B}}(B_s \to \mu\mu)^{\text{SM}} = (3.65 \pm 0.23) \times 10^{-9}$$

- Anomalies in $B \to K^*\mu^+\mu^-$ angular distributions $\Rightarrow$ yesterday talks.

Explaining R_K

If the LFUV takes place at scales well above EWSB, then use OPE:

- Operators relevant to $b \to s\ell\ell$ are

$$\boldsymbol{\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)}, \qquad \boldsymbol{\mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma^5 \ell)},$$
$$\mathcal{O}_S^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\ell), \qquad \mathcal{O}_P^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell),$$
$$\mathcal{O}_7^{(\prime)} = (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu} \quad \ldots$$

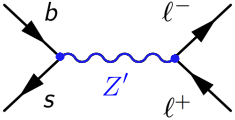
- To explain $R_K < 1$, one needs effective coefficients $C_9^{(\prime)}$, $C_{10}^{(\prime)}$ different from the SM values.

- Compatible with results based on the global fits of $b \to s\ell\ell$ data. [Straub et al. 2014, Descotes-Genon et al. 2015, Hurth et al. 2016]

Are there **specific models** capable of generating $C_{9,10}^{(\prime)}$ to explain R_K?

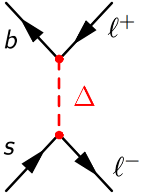
Representative models:

Z' models



Buras et al., Altmannshofer et al., Crivellin et al., Celis et al. ...

Leptoquark models



Hiller et al., Becirevic et al., Gripaios et al. ...

- Vector leptoquark models also plausible, but non-renormalizable [problematic, how to compute loops? $B_s - \bar{B}_s$ constraint?]

  Barbieri et al., Fajfer et al.

- Interesting feature: **LFV** is in general **expected** .

Explaining R_K: Illustration

Scalar Leptoquark Models

Analysis of the separate modes: data **prefers** to decrease $\mathcal{B}(B^+ \to K^+ \mu\mu)$.

$\Rightarrow$ Let us focus on NP with couplings only to muons

[although couplings to electrons are also possible, cf. Hiller, Schmaltz 2014]

Representation under $SU(3)_c \times SU(2)_L \times U(1)_Y$:

- $(3,2)_{7/6}$: Increases $B \to K\mu^+\mu^-$ $\quad (C_9)_{\mu\mu} = (C_{10})_{\mu\mu} \quad \bar{Q}\Delta^{(7/6)}\ell_R$
- $\mathbf{(3,2)_{1/6}}$: Decreases $B \to K\mu^+\mu^-$ $\quad (C_9')_{\mu\mu} = -(C_{10}')_{\mu\mu} \quad \bar{L}\widetilde{\Delta}^{(1/6)}d_R$
- $(\bar{3},3)_{1/3}$ and $(3,1)_{4/3}$ $\Rightarrow$ Proton destabilizes

[Kosnik, 2012]

NB. Convention: $Q = T_3 + Y$.

Explaining R_K: Illustration

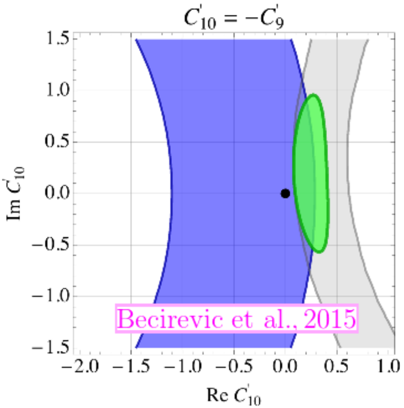
Scalar Leptoquark $(3,2)_{1/6}$

1st step: Wilson coefficients fit.

$\mathcal{B}(B_s \to \mu^+\mu^-)$ and $\mathcal{B}(B^+ \to K^+\mu\mu)_{\text{high } q^2}$

$\Rightarrow (C'_{10})_{\mu\mu} = -(C'_9)_{\mu\mu} \in (0.19, 0.52)$

$\Rightarrow \mathbf{R_K^{pred} = 0.88(8)}$.



Model independent prediction: $\boldsymbol{R_{K^*} = 1.11(8)}$

[RH quark currents imply $R_{K^*} > 1$]

[Hiller, Schmaltz 2014]

2nd step: Model dependent interpretation.

$$\mathcal{L}_Y = \boldsymbol{Y_{ij}} \bar{L}_{Li} \widetilde{\Delta}^{(1/6)} d_{Rj} + \text{h.c.}$$

$$\mathbb{Y} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \boldsymbol{Y_{\mu s}} & \boldsymbol{Y_{\mu b}} \\ 0 & & \end{pmatrix}$$

$$C_9' = -C_{10}' \propto \frac{Y_{\mu s} Y_{\mu b}^*}{m_\Delta^2}$$

Explaining R_K: Illustration

Scalar Leptoquark $(3,2)_{1/6}$

2nd step: Model dependent interpretation.

$$\mathcal{L}_Y = \boldsymbol{Y_{ij}} \bar{L}_{Li} \widetilde{\Delta}^{(1/6)} d_{Rj} + \text{h.c.}$$

$$\mathbb{Y} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \boldsymbol{Y_{\mu s}} & \boldsymbol{Y_{\mu b}} \\ 0 & \boldsymbol{Y_{\tau s}} & \boldsymbol{Y_{\tau b}} \end{pmatrix}$$

$$C_9' = -C_{10}' \propto \frac{Y_{\mu s} Y_{\mu b}^*}{m_\Delta^2}$$

How can we probe the couplings to τ's?

- $\tau \to \mu\phi$ is an useful constraint
- **LFV** in $B_{(s)}$ decays.!

Outline

- OPE for LFV:

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}_1\gamma^\mu \ell_2), \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}_1\gamma^\mu\gamma^5 \ell_2),$$
$$\mathcal{O}_S^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}_1 \ell_2), \qquad \mathcal{O}_P^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}_1\gamma_5 \ell_2),$$
$$\mathcal{O}_7^{(\prime)} = (\bar{s}\sigma_{\mu\nu} P_{R(L)} b)F^{\mu\nu} \quad \dots$$

- Let us focus on scenarios with $C_{9,10}^{(\prime)} \neq 0$ (SLQ and Z').
- $C_{S,P}^{(\prime)} \neq 0 \Rightarrow$ We used CMS hint $\mathcal{B}(h \to \tau\mu) = 0.83(38)\%$ to fix the couplings and obtained that LFV in B decays is too small ($\lesssim 10^{-13}$).

- Attention: $i\partial_\mu(\bar{\ell}_1\gamma^\mu\ell_2) = (m_2 - m_1)\bar{\ell}_1\ell_2 \neq 0$

  $\Rightarrow$ New contributions appear in the LFV modes

$$\mathcal{B}(B_s \to \ell_1^-\ell_2^+) \propto [m_{B_s}^2 - (m_1+m_2)^2](m_1 - m_2)^2 \cdot |C_9 - C_9'|^2 + [m_{B_s}^2 - (m_1 - m_2)^2](m_1+m_2)^2 \cdot |C_{10} - C_{10}'|^2$$

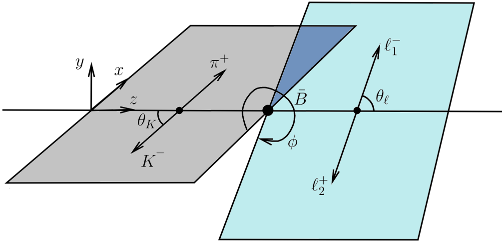
- $C_9^{(\prime)} = -C_{10}^{(\prime)} \neq 0$ $\Rightarrow$ Hierarchy between modes:

$$\mathcal{B}(B_s \to \ell_1\ell_2) < \mathcal{B}(B \to K\ell_1\ell_2) < \mathcal{B}(B \to K^*\ell_1\ell_2)$$

$$\frac{\mathcal{B}(B \to K^*\mu\tau)}{\mathcal{B}(B \to K\mu\tau)} \approx 1.8, \qquad \frac{\mathcal{B}(B \to K\mu\tau)}{\mathcal{B}(B_s \to \mu\tau)} \approx 1.25.$$

- **Important**: Limits on one exclusive LFV mode can set constraints on the others.

- Most theory papers do not provide the full angular conventions for $\bar{B} \to \bar{K}^*\ell\ell$ [ambiguity in the definition of ϕ].
- We adopt the conventions of [Gratrex et al., 2015] $\equiv$ LHCb and find full agreement for $I_i(q^2)$.



K^* rest frame:

$$p_K^\mu = (E_K, \hat{\mathbf{p}}_\mathbf{K}|p_K|), \quad p_\pi^\mu = (E_\pi, -\hat{\mathbf{p}}_\mathbf{K}|p_K|),$$

with $\hat{\mathbf{p}}_\mathbf{K} = (-\sin\theta_K, 0, -\cos\theta_K)$.

Dilepton rest frame:

$$p_1^\mu = (E_\alpha, \hat{\mathbf{p}}_\ell|p_\ell|), \quad p_2^\mu = (E_\beta, -\hat{\mathbf{p}}_\ell|p_\ell|),$$

with $\hat{\mathbf{p}}_\ell = (\sin\theta_\ell\cos\phi, -\sin\theta_\ell\sin\phi, \cos\theta_\ell)$.

- LFC case $(m_1 = m_2)$ – $A^{L,R}_{\parallel,\perp,0}$ and $A_{S,P}$:

$$\bar{\ell}\gamma_5\ell = \frac{q^\mu(\bar{\ell}\gamma_\mu\gamma_5\ell)}{2m_\ell} \quad \Rightarrow \quad C_{P(\prime)} \text{ can be absorbed in } A_t.$$

$$q^\mu(\bar{\ell}\gamma_\mu\ell) = 0 \quad \Rightarrow \quad C_{S(\prime)} \text{ require a \underline{residual HA} } A_S.$$

- LFV case $(m_1 \neq m_2)$ – $A^{L,R}_{\parallel,\perp,0,t}$:

$$\bar{\ell}_1\gamma_5\ell_2 = \frac{q^\mu(\bar{\ell}_1\gamma_\mu\gamma_5\ell_2)}{m_1+m_2}, \quad \bar{\ell}_1\ell_2 = \frac{q^\mu(\bar{\ell}_1\gamma_\mu\ell_2)}{m_1-m_2} \quad \Rightarrow \quad \text{New HA's } A_t^{L,R}$$

- LFC case $(m_1 = m_2)$ – $A^{L,R}_{\|,\perp,0}$ and $A_{S,P}$:

$$\bar\ell\gamma_5\ell = \frac{q^\mu(\bar\ell\gamma_\mu\gamma_5\ell)}{2m_\ell} \quad \Rightarrow \quad C_{P(\prime)} \text{ can be absorbed in } A_t.$$

$$q^\mu(\bar\ell\gamma_\mu\ell) = 0 \quad \Rightarrow \quad C_{S(\prime)} \text{ require a residual HA } A_S.$$

- LFV case $(m_1 \neq m_2)$ – $A^{L,R}_{\|,\perp,0,t}$:

$$\bar\ell_1\gamma_5\ell_2 = \frac{q^\mu(\bar\ell_1\gamma_\mu\gamma_5\ell_2)}{m_1+m_2}, \quad \bar\ell_1\ell_2 = \frac{q^\mu(\bar\ell_1\gamma_\mu\ell_2)}{m_1-m_2} \quad \Rightarrow \quad \text{New HA's } A_t^{L,R}$$

Going from LFC to LFV:

$$A_t = \lim_{m_1\to m_2}\left(A_t^L - A_t^R\right), \qquad A_S = \lim_{m_1\to m_2}\left[\frac{m_1-m_2}{\sqrt{q^2}}\left(A_t^L + A_t^R\right)\right]$$

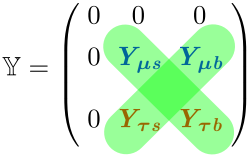
NB. The singularity in $m_1 = m_2$ cancels out in $I_i(q^2)$.

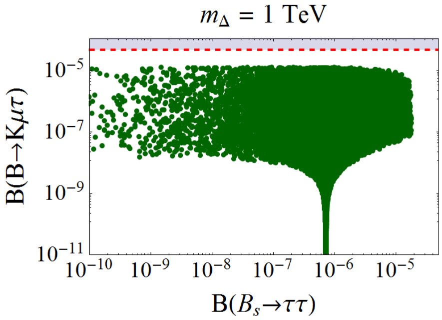
Maximally allowed value lies just below the BaBar limit: $\mathcal{B}(B^+ \to K^+\mu\tau) \le 4.8 \times 10^{-5}$ [90% CL.].

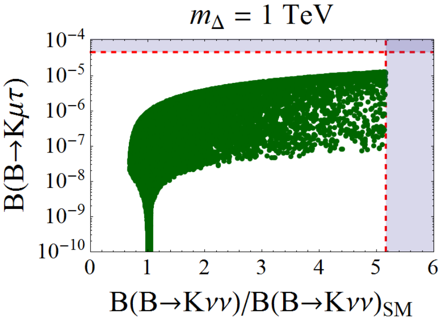
[Becirevic et al., to appear]

Can LHCb do better ?

Even weak limits on $B \to K\mu\tau$ can be useful to constraint $\boldsymbol{Y}_{\tau s}$, $\boldsymbol{Y}_{\tau b}$ and $B \to K\nu\nu$ (Belle-2).







Explaining R_K: Another Possibility

Z' Models

Z' bosons are usually associated with a new Abelian symetry $U(1)'$.

A few examples:

- Gauged $L_\mu - L_\tau$ symmetry [Crivellin, D'Ambrosio, Heeck, 1501.00993]
- Gauged $B - L$ charges [Crivellin, D'Ambrosio, Heeck, 1503.03477]

Here, we will consider a bottom-up approach:

$\Rightarrow$ Z' couplings are only **fixed by data**.

[Crivellin et al. 2015, Becirevic et al. 2016]

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

Assumptions: gauge invariance (e.g., $g^L_{\ell_i \ell_j} = g^L_{\nu_i,\nu_j}$) and no couplings to electrons.

- Scenario I: $g_{sb}^L, g_{\mu\mu}^L \neq 0$ $\quad (C_9)_{\mu\mu} = -(C_{10})_{\mu\mu} \propto g_{sb}^L g_{\mu\mu}^L$.
- Scenario II: $g_{sb}^R, g_{\mu\mu}^L \neq 0$ $\quad (C_9')_{\mu\mu} = -(C_{10}')_{\mu\mu} \propto g_{sb}^R g_{\mu\mu}^L$.

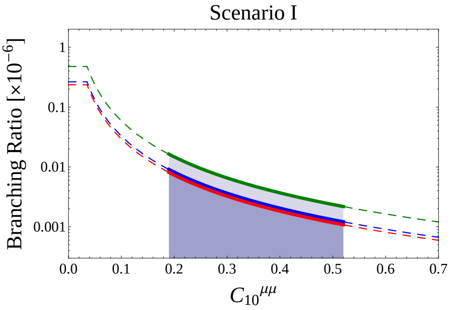
$$\mathcal{L}_{Z'} \supset \boldsymbol{g_{\ell_i\ell_j}^L} \bar{\ell}_i \gamma^\mu P_L \ell_j Z'_\mu + \boldsymbol{g_{sb}^L} \bar{s}\gamma^\mu P_L b Z'_\mu + (L \to R)$$

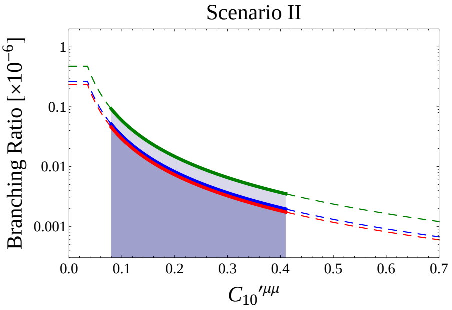
Most relevant constraints:

$B_s - \bar{B}_s$ mixing	$\Longleftrightarrow$	$\lvert g_{sb}^{L(R)}\rvert / m_{Z'} \leq 1.6 \times 10^{-3}\ \mathrm{TeV}^{-1}$
$\tau \to \mu\bar{\nu}_\mu\nu_\tau$	$\Longleftrightarrow$	$(g_{\mu\mu}^L, g_{\mu\tau}^L, g_{\mu\tau}^R)/m_{Z'}$
$\tau \to 3\mu$	$\Longleftrightarrow$	$(g_{\mu\tau}^L, g_{\mu\tau}^R)/m_{Z'}$

Maximal branching ratios $\Rightarrow$ Possibly within the reach of LHCb and Belle-2.

Scenario	I (LH)	II (RH)
$\mathcal{B}(B \to K^*\mu\tau) \leq$	1.6×10^{-8}	9.3×10^{-8}
$\mathcal{B}(B \to K\mu\tau) \leq$	0.9×10^{-8}	5.2×10^{-8}
$\mathcal{B}(B_s \to \mu\tau) \leq$	0.8×10^{-8}	4.6×10^{-8}





Outline

Brief discussion of $h \to \mu\tau$

Higgs LFV Coupling

[Becirevic et al. 2015]

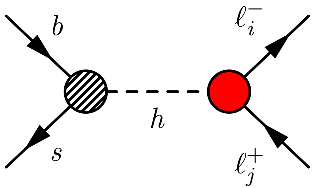
- CMS observed $\mathcal{B}(h \to \tau\mu) = 0.846^{+0.39}_{-0.37}\%$ $[2.2\sigma]$. What are the implications for B physics if this result is confirmed?

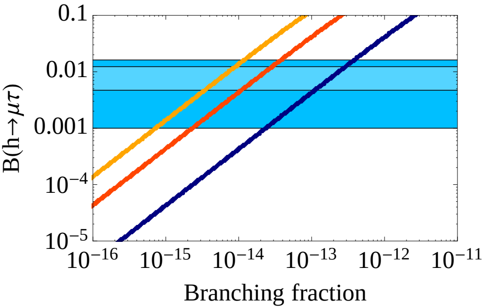
Brief discussion of $h \to \mu\tau$

Higgs LFV Coupling [Becirevic et al. 2015]

- CMS observed $\mathcal{B}(h \to \tau\mu) = 0.846^{+0.39}_{-0.37}\%$ [2.2σ]. What are the implications for B physics if this result is confirmed?

$$\mathcal{L}_{\rm eff} = -y_{ij}\,\bar{\ell}^i_L \bar{\ell}^j_R h + \text{h.c.} \quad \Leftrightarrow \quad 0.8 \times 10^{-3} < \sqrt{|y_{\mu\tau}|^2 + |y_{\tau\mu}|^2} < 3.6 \times 10^{-3}$$





Largest BR is $\mathcal{B}(B_s \to \mu\tau) < 4 \times 10^{-13} \Rightarrow$ Too small!

Outline

Conclusions and Perspectives

- Interesting hints of LFU violation in R_K and $R_{D^{(*)}}$ – Higgs Flavor Era around the corner?
- Important cross-checks: R_{K^*}, R_ϕ, $\mathcal{B}(B_s \to D_s \tau \bar{\nu})/\mathcal{B}(B_s \to D_s \ell \bar{\nu})$ etc [theoretically and experimentally clean].
- LFV is expected in most models aiming to explain R_K. We give predictions in models with generic Z' states ($\sim 10^{-7}$) and SLQ ($\sim 10^{-5}$).
- Take-home message: even not so stringent experimental limits on exclusive B LFV decay modes can be useful to constrain models of NP.

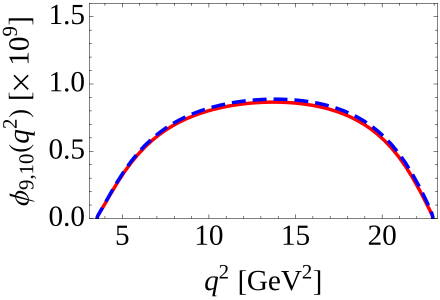
Thank you!

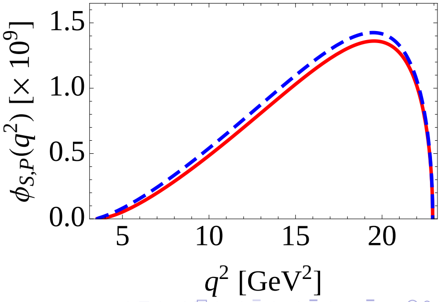
Back-up

$$\mathcal{B}(B_s \to \ell_1^- \ell_2^+)^{theo} = \frac{\tau_{B_s}}{64\pi^3} \frac{\alpha^2 G_F^2}{m_{B_s}^3} f_{B_s}^2 |V_{tb} V_{ts}^*|^2 \lambda^{1/2}(m_{B_s}, m_1, m_2)$$

$$\times \left\{ [m_{B_s}^2 - (m_1 + m_2)^2] \cdot \left| (C_9 - C_9')(m_1 - m_2) + (C_S - C_S') \frac{m_{B_s}^2}{m_b + m_s} \right|^2 \right.$$

$$\left. + [m_{B_s}^2 - (m_1 - m_2)^2] \cdot \left| (C_{10} - C_{10}')(m_1 + m_2) + (C_P - C_P') \frac{m_{B_s}^2}{m_b + m_s} \right|^2 \right\}$$





SLQ $(3,2)_{1/6}$

$$C_{9'}^{\ell\ell'} = -C_{10'}^{\ell\ell'} = \frac{\pi v^2}{2\lambda_t \alpha_{\rm em}} \frac{Y_{s\ell} Y_{b\ell'}^*}{m_\Delta^2},$$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2}(B \to K\nu\bar{\nu}) = \frac{|N|^2}{384\pi^3 m_B^3} |f_+(q^2)|^2 \lambda^{3/2}(m_B^2, m_K^2, q^2) \times \left\{ 3|C_L^{\rm SM}|^2 + \frac{(Y\cdot Y^\dagger)_{ss}(Y\cdot Y^\dagger)_{bb}}{16N^2 m_\Delta^4} + \frac{2{\rm Re}[C_L^{\rm SM}(Y\cdot Y^\dagger)_{sb}]}{4N m_\Delta^2} \right\},$$

where $N = \dfrac{G_F V_{tb} V_{ts}^* \alpha}{\sqrt{2}\pi}$ and $C_L^{\rm SM} = -6.38(6)$.

LFV in $b \to s\mu\tau$

Z' Models – Comments on [Crivellin et al. 1504.07928]

Similar scenarios are considered: $C_9^{\mu\mu} \neq 0$ and $C_9^{\mu\mu} = -C_{10}^{\mu\mu} \neq 0$; but the rates are ten times larger. Why?

- 2σ discrepancy in $\mathcal{B}(\tau \to \mu\nu\bar{\nu})$?

$$\mathcal{B}(\tau \to \mu\nu\bar{\nu})_{\mathrm{SM}} = 17.29(3)\%$$
$$\mathcal{B}(\tau \to \mu\nu\bar{\nu})_{\mathrm{exp}} = 17.33(5)\% \quad \text{[Average]}$$
$$\mathcal{B}(\tau \to \mu\nu\bar{\nu})_{\mathrm{exp}} = 17.41(4)\% \quad \text{[Fit]}$$

  PDG and HFAG fits amplify the 1.6σ discrepancy of

$$\mathcal{B}(\tau \to \mu\nu\bar{\nu})/\mathcal{B}(\tau \to e\nu\bar{\nu})$$

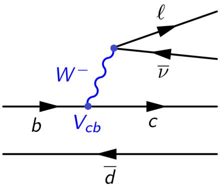
  measured by BaBar $\Rightarrow$ The average should be used instead.

- Main source of disagreement: $B_s - \bar{B}_s$ mixing

  If $b \to s\mu\mu$ data is analyzed with only $C_{9,10}$, then $g_{sb}^R = 0 \Rightarrow$ No fine-tuning in $B_s - \bar{B}_s$.

- Tree-level process in the SM:

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}, \quad \ell = e, \mu.$$



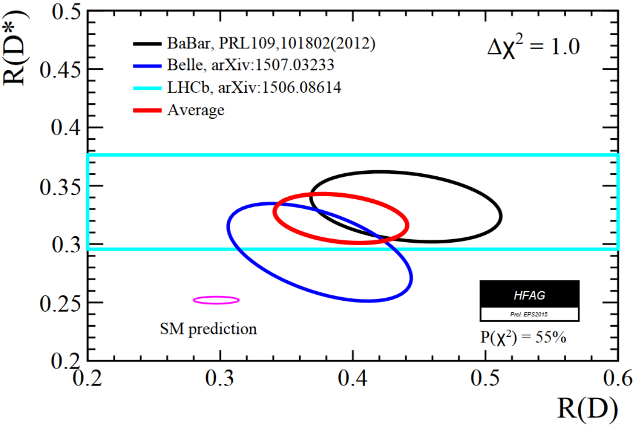
- Non-perturbative QCD $\Longleftrightarrow$ form-factors (Lattice QCD)

e.g. for $B \to D$, $\langle D|\bar{c}\gamma_\mu b|B\rangle \propto f_{0,+}(q^2)$

- Situation less clear for $B \to D^*$ $\Rightarrow$ (more FFs, less LQCD results)
[One form factor is unknown from LQCD (error associated?)]

LFU violation

(ii) $b \to c\tau\bar{\nu}$



- 3.9σ combined deviation from the SM [theory error under control?]
- 2σ deviation if only R_D is considered.