LFV in B decays

Diego Guadagnoli
LAPTh Annecy (France)

Based on
S.L. Glashow, DG, K. Lane,
PRL 15
Motivation: LHCb’s $b \to s$ data

The original reason for this work are the following pieces of exp info (LHCb):

\[ R_K = \frac{BR(B^+ \to K^+ \mu \mu)_{[1,6]}}{BR(B^+ \to K^+ e e)_{[1,6]}} = 0.745 \cdot (1 \pm 13\%) \]

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2. \[ BR(B^+ \to K^+ \mu \mu)_{[1,6]}^{[1,6]} = (1.19 \pm 0.07) \cdot 10^{-7} \]
   vs.
\[ BR(B^+ \to K^+ \mu \mu)_{[1,6]}^{SM} = 1.75^{+0.60}_{-0.29} \times 10^{-7} \]

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1 + 2 + 3 $\Rightarrow$ There seems to be BSM LFNU and the effect is in $\mu\mu$, not $ee$
Actually, after some effective-theory insights, two further pieces of info support the above picture.

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Yet:
- **Q1**: Can we (easily) make sense of ① to ⑤?
- **Q2**: What are the most immediate signatures to expect?
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- If $R_K$ is signaling LFNU at a non-SM level, we may also expect LFV at a non-SM level.
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- Consider a new, LFNU interaction above the EWSB scale, e.g. with

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  new vector bosons: $l\ell' Z'$ or leptoquarks: $l\phi q$

- *In what basis are quarks and leptons in the above interaction?*
  
  *In general, it's the “gauge” basis.*
  
  *Namely, it's not the mass eigenbasis.*
  
  *(This basis doesn't yet even exist. We are above the EWSB scale.)*
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- Rotating $q$ and $\ell$ to the mass eigenbasis generates LFV interactions.
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Consider the following Hamiltonian

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H_{\text{SM+NP}}(\bar{b} \rightarrow \bar{s} \mu \mu) = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \frac{\alpha_{\text{em}}}{4\pi} \left[ \bar{b}_L \gamma^\lambda s_L \cdot \left( C_{9}^{(\mu)} \bar{\mu} \gamma^\lambda \mu + C_{10}^{(\mu)} \bar{\mu} \gamma^\lambda \gamma^5 \mu \right) \right]
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purely vector lepton current

purely axial lepton current
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\]

- Note:
\[
C_9^{SM} (m_b) \approx +4.2 \\
C_{10}^{SM} (m_b) \approx -4.4
\]

[Bobeth, Misiak, Urban, 99] 
[Khodjamirian et al., 10]
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Note: In the SM, also the lepton current has nearly V - A structure.

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Note:

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C^\text{SM}_{9}(m_b) \approx +4.2 \\
C^\text{SM}_{10}(m_b) \approx -4.4
\]

i.e. in the SM also the lepton current has nearly V – A structure.

We assume the above V – A structure to hold also beyond the SM, namely

\[
C^{(\ell)}_9 \approx -C^{(\ell)}_{10} \quad \text{with} \quad C^{(\ell)}_{9,10} = C^{\text{SM}}_{9,10} + C^{(\ell),\text{NP}}_{9,10}
\]

Our main motivation is phenomenological: it fits the data. However, there is more: see last slide.

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In short, our model requirements are:

- $C_9^{(\ell)} \approx -C_{10}^{(\ell)}$ (V – A structure)

- $|C_{9,\text{NP}}^{(\mu)}| \gg |C_{9,\text{NP}}^{(e)}|$ (LFNU)
In short, our model requirements are:

\[ C_9^{(\ell)} \approx -C_{10}^{(\ell)} \quad (V-A \text{ structure}) \]

\[ |C_{9,NP}^{(\mu)}| \gg |C_{9,NP}^{(e)}| \quad (LFNU) \]

This structure can be generated from a purely 3rd-generation interaction of the kind

\[
H_{NP} = G \bar{b}'_L y^\lambda_b b'_L \bar{\tau}'_L y^\lambda \tau'_L
\]

with \( G = 1/\Lambda_{NP}^2 \ll G_F \)

expected e.g. in topcolor models

[see C.T. Hill, PLB 1995]
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Note: primed fields

Fields are in the “gauge” basis (= primed)
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- Fields are in the “gauge” basis (= primed)
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\[ b_L' \equiv (d_L')_3 = |U_L^d|_{3i} (d_L)_i \]

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In short, our model requirements are:

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**Note:** primed fields

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- This rotation induces LFNU and LFV effects

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\begin{align*}
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Explaining $b \to s$ data

- Recalling our full Hamiltonian

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

the shift to the $C_9$ Wilson coeff. in the $\mu\mu$-channel becomes

$$k_{\text{SM}} C_9^{(\mu)} = k_{\text{SM}} C_{9,\text{SM}} + \frac{G}{2} \left( U_{L}^{d*} (U_{L}^{d})_3 \right)_2^2$$
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$k_{\text{SM}}$ (SM norm. factor)
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$$= \beta_{\text{SM}}$$
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$$= \beta_{SM} + \beta_{NP}$$

The NP contribution has opposite sign than the SM one if

$$G \left( (U_L^d)_{32} \right) < 0$$
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\]

The NP contrib. in the ee-channel is negligible, as

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- The above shifts to the $C_{9,10}$ Wilson coeffs. imply

$$R_K \approx \frac{|C_9^{(\mu)}|^2 + |C_{10}^{(\mu)}|^2}{|C_9^{(e)}|^2 + |C_{10}^{(e)}|^2} = \frac{2 \cdot (\beta_{SM} + \beta_{NP})^2}{2 \cdot \beta_{SM}^2}$$
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Approximations

- phase-space factor is about the same in the $\mu\mu$- and in the $ee$-channel
- dominance of the $|C_{9,10}|^2$ contributions in the concerned $q^2$ region
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- Note as well

$$0.77 \pm 0.20 = \frac{BR(B_s \rightarrow \mu\mu)_{\text{exp}}}{BR(B_s \rightarrow \mu\mu)_{\text{SM}}} = \frac{BR(B_s \rightarrow \mu\mu)_{\text{SM+NP}}}{BR(B_s \rightarrow \mu\mu)_{\text{SM}}} = \frac{(\beta_{\text{SM}} + \beta_{\text{NP}})^2}{\beta_{\text{SM}}^2}$$

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Explain b → s data

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  - dominance of the $|C_{9,10}|^2$ contributions in the concerned $q^2$ region

- Note as well

$$0.77 \pm 0.20 = \frac{BR(B_s \rightarrow \mu\mu)_{exp}}{BR(B_s \rightarrow \mu\mu)_{SM}} = \frac{BR(B_s \rightarrow \mu\mu)_{SM+NP}}{BR(B_s \rightarrow \mu\mu)_{SM}} = \frac{(\beta_{SM} + \beta_{NP})^2}{\beta_{SM}^2}$$

implying (within our model) the correlations

$$\frac{BR(B_s \rightarrow \mu\mu)_{exp}}{BR(B_s \rightarrow \mu\mu)_{SM}} \approx R_K \approx \frac{BR(B^+ \rightarrow K^+ \mu\mu)_{exp}}{BR(B^+ \rightarrow K^+ \mu\mu)_{SM}}$$

Another good reason to pursue accuracy in the $B_s \rightarrow \mu\mu$ measurement

D. Guadagnoli, LFV in B decays
\[
\frac{BR(B^+ \to K^+ \mu e)}{BR(B^+ \to K^+ \mu \mu)} = \frac{\beta_{NP}^2}{(\beta_{SM} + \beta_{NP})^2} \cdot \frac{|(U^L_{\ell 31})|^2}{|(U^L_{\ell 32})|^2} \cdot 2
\]
\[ \frac{BR(B^+ \to K^+ \mu e)}{BR(B^+ \to K^+ \mu \mu)} = \frac{\beta_{NP}^2}{(\beta_{SM} + \beta_{NP})^2} \frac{|(U_L^\ell)_{31}|^2}{|(U_L^\ell)_{32}|^2} \cdot 2 \]

\[ = 0.159^2 \]

according to \( R_K \)
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**LFV model signatures**

\[
\frac{BR(B^+ \rightarrow K^+ \mu e)}{BR(B^+ \rightarrow K^+ \mu \mu)} = \frac{\beta_{NP}^2}{(\beta_{SM} + \beta_{NP})^2} \left| \begin{pmatrix} U_L^{\ell} \end{pmatrix}_{31} \right|^2 \left| \begin{pmatrix} U_L^{\ell} \end{pmatrix}_{32} \right|^2 \cdot \frac{2}{\mu^e - \mu^e \text{ modes}}
\]

The current \( BR(B^+ \rightarrow K^+ \mu e) \) limit yields the weak bound

\[
\left| \begin{pmatrix} U_L^{\ell} \end{pmatrix}_{31} \right| \left| \begin{pmatrix} U_L^{\ell} \end{pmatrix}_{32} \right| < 3.7
\]
**LFV model signatures**

\[
\frac{BR(B^+ \to K^+ \mu e)}{BR(B^+ \to K^+ \mu \mu)} = \frac{\beta_{NP}^2}{(\beta_{SM} + \beta_{NP})^2} \left| \frac{(U_L^\ell)_{31}}{(U_L^\ell)_{32}} \right|^2 \cdot 2 \mu^*e^{-} & \mu^{-}e^{+} \text{ modes}
\]

\[
BR(B^+ \to K^+ \mu e) < 2.2 \times 10^{-8} \cdot \left| \frac{(U_L^\ell)_{31}}{(U_L^\ell)_{32}} \right|^2
\]

The current \(BR(B^+ \to K^+ \mu e)\) limit yields the weak bound

\[
\left| \frac{(U_L^\ell)_{31}}{(U_L^\ell)_{32}} \right| < 3.7
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\[
BR(B^+ \to K^+ \mu \tau) \text{ would be even more promising, as it scales with } \left| \frac{(U_L^\ell)_{33}}{(U_L^\ell)_{32}} \right|^2
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**LFV model signatures**

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\]

with \( \beta_{NP} = 0.159^2 \) according to \( R_K \).

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BR(B^+ \to K^+ \mu e) < 2.2 \times 10^{-8} \cdot \left| \frac{(U_L^\ell)_{31}}{(U_L^\ell)_{32}} \right|^2
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\[
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\]

would be even more promising, as it scales with \( \left| \frac{(U_L^\ell)_{33}}{(U_L^\ell)_{32}} \right|^2 \)

A reliable prediction of the BR requires more work, especially because of

- terms other than \( |C_9|^2 \) and \( |C_{10}|^2 \) are important
- phase-space factors are substantially different than in the \( \mu \mu \) and ee cases
\[ \frac{BR(B_s \rightarrow \mu e)}{BR(B_s \rightarrow \mu \mu)} = \frac{\beta_{NP}^2}{(\beta_{SM} + \beta_{NP})^2} \cdot \frac{|(U_L^f)_{31}|^2}{|(U_L^f)_{32}|^2} \]
$\frac{BR(B_s \to \mu e)}{BR(B_s \to \mu \mu)} = \frac{\beta_{NP}^2}{(\beta_{SM} + \beta_{NP})^2} \cdot \frac{|(U_L^e)_{31}|^2}{|(U_L^e)_{32}|^2}$

Again, $B_s \to \mu \tau$ would be even more promising, because it scales as $|(U_L^e)_{33}|^2/(U_L^e)_{32}|^2$

(a potential enhancement factor, actually)
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\frac{BR(B_s \to \mu e)}{BR(B_s \to \mu \mu)} = \frac{\beta_{NP}^2}{(\beta_{SM} + \beta_{NP})^2} \cdot \frac{|(U_L^\ell)_{31}|^2}{|(U_L^\ell)_{32}|^2}
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Again, \( B_s \to \mu \tau \) would be even more promising, because it scales as \( |(U_L^\ell)_{33}|^2/(U_L^\ell)_{32}|^2 \)

(a potential enhancement factor, actually)

An interesting signature outside B physics would be \( K \to \pi \ell^- \ell^+ \)

Note, instead, that the “K-physics analogue” of \( R_K \):

\[
\frac{BR(K \to \pi \mu \mu)}{BR(K \to \pi e e)} \quad \text{less interesting}
\]

as it is long-distance dominated

[see D'Ambrosio et al., 1998]
More signatures

- Being defined above the EWSB scale, our assumed operator \( G \bar{b}'_L \gamma^\lambda b'_L \bar{\tau}'_L \gamma^\lambda \tau'_L \)
  must actually be made invariant under \( SU(3)_c \times SU(2)_L \times U(1)_Y \).
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\[
\bar{b}'_L \gamma^\lambda b'_L \bar{\tau}'_L \gamma^\lambda \tau'_L \quad \text{inv.} \quad \begin{cases} 
\bar{Q}'_L \gamma^\lambda Q'_L \bar{L}'_L \gamma^\lambda L'_L \\
\bar{Q}'^i_L \gamma^\lambda Q'^j_L \bar{L}'^i_L \gamma^\lambda L'^j_L \\
\bar{Q}'^i_L \gamma^\lambda Q'^j_L \bar{L}'^i_L \gamma^\lambda L'^j_L
\end{cases}
\]

[neutral-current int's only]
[also charged-current int's]

See:
Bhattacharya, Datta, London, Shivashankara, PLB 15

For a recent discussion:
Alonso, Grinstein, Martin-Camalich, PRL 14
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See: Bhattacharya, Datta, London, Shivashankara, PLB 15

For a recent discussion: Alonso, Grinstein, Martin-Camalich, PRL 14

\[
\begin{aligned}
&\overline{b}'_L \gamma^\lambda b'_L \bar{\tau}'_L \gamma^\lambda \tau'_L \\
\text{inv.} \\
&\text{SU(2)}_L \\
&\begin{cases}
\overline{Q}'_L \gamma^\lambda Q'_L \bar{L}'_L \gamma^\lambda L'_L & \text{[neutral-current int's only]} \\
\overline{Q}''^i_L \gamma^\lambda Q''^j_L \bar{L}'^i_l \gamma^\lambda L''^i_l & \text{[also charged-current int's]}
\end{cases}
\end{aligned}
\]

- Thus, the generated structures are all of:

\[
\begin{aligned}
t't' \nu'_{\tau} \nu'_{\tau}, & \quad t't' \tau' \tau', & \quad b'b' \nu'_{\tau} \nu'_{\tau}, & \quad b'b' \tau' \tau', & \quad t'b' \tau' \nu'_{\tau}
\end{aligned}
\]
More signatures

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\end{aligned}
\end{align*}
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\[ \begin{align*}
\bar{b}'_L \gamma^\lambda b'_L \bar{\tau}'_L \gamma^\lambda \tau'_L & \rightarrow SU(2)_L \\
\{ & \begin{align*}
\bar{Q}'_L \gamma^\lambda Q'_L \bar{L}'_L \gamma^\lambda L'_L \\
\bar{Q}'_L \gamma^\lambda Q'_L \bar{L}'_L \gamma^\lambda L'_L & \text{[neutral-current int's only]} \\
\bar{Q}'^i_L \gamma^\lambda Q'^j_L \bar{L}'^i_L \gamma^\lambda L'^j_L & \text{[also charged-current int's]} \\
\end{align*}
\end{align*} \]

Thus, the generated structures are all of:

- $t't' \nu'_\tau \nu'_\tau$, $t't' \tau' \tau'$, $b'b' \nu'_\tau \nu'_\tau$, $b'b' \tau' \tau'$, $t'b' \tau' \nu'_\tau$

After rotation to the mass basis (unprimed), the last structure contributes to $\Gamma(b \to c \tau \bar{\nu}_i)$

Can explain BaBar deviations on $R(D^{(*)}) = \frac{BR(\bar{B} \to D^{(*)+} \tau^- \bar{\nu}_\tau)}{BR(\bar{B} \to D^{(*)+} e^- \bar{\nu}_e)}$
Spares
Frequently made objection: what about the SM? It has LFNU, but no LFV

Take the SM with zero $\nu$ masses.

- Charged-lepton Yukawa couplings are LFNU, but they are diagonal in the mass eigenbasis (hence no LFV)
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Bottom line: in the $SM+\nu$ there is LFNU, but LFV is nowhere to be seen (in decays)
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Bottom line: in the SM+$\nu$ there is LFNU, but LFV is nowhere to be seen (in decays)

- But nobody ordered that the reason (=tiny $m_\nu$) behind the above conclusion be at work also beyond the SM

So, BSM LFNU $\Rightarrow$ BSM LFV (i.e. not suppressed by $m_\nu$)