Footprints of LQs: from $B$ to $K$ rare decays

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Nov 1st, 2017

[arXiv:1711.xxxxx [hep-ph]], in collaboration with Svjetlana Fajfer and Nejc Košnik (Institut Jožef Stefan)

NExT Physics Meeting, RHUL
Outline

1. Introduction
2. NP for $B$-anomalies
3. Pheno of two LQ models
4. $s \rightarrow d\nu\nu$ transitions
$B$-physics anomalies

SM LFU (Lepton Flavor Universality) respected to a very good extent
Pattern of deviations w.r.t. the SM $\rightarrow$ NP LFUV

**Neutral Currents**

$$R_{K^*(\ast)} = \frac{\mathcal{B}(B\to K(\ast)\mu^+\mu^-)}{\mathcal{B}(B\to K(\ast)e^+e^-)}$$

BRs and angular obs. in $b \to s\mu^+\mu^-$

$\sim 2.1 - 2.6\sigma$ (w/ SM)

$\sim 2.2 - 2.9\sigma$ (w/ SM)

**Charged Currents**

$$R_{D(\ast)} = \frac{\mathcal{B}(B^0\to D(\ast)^-\tau^+\nu)}{\mathcal{B}(B^0\to D(\ast)^-\ell^+\nu)}$$

$$R_{J/\psi} = \frac{\mathcal{B}(B_{c}^{+}\to (J/\psi)\tau^+\nu)}{\mathcal{B}(B_{c}^{+}\to (J/\psi)\mu^+\nu)}$$

$\sim 2 - 3.4\sigma$ (w/ SM)

$\sim 2\sigma$ (w/ SM)
Possible EFT interpretations

N.C. : $\mathcal{L}_{b \rightarrow s \ell \ell}^{NP} \supset 4 \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \left[ \delta^\ell \bar{s} \gamma_\rho P_L b \cdot \bar{\ell} \gamma_\rho (1 - \gamma_5) \ell \right] + h.c.$

[Altmannshofer+'17, Capdevila+'17, L.-S. Geng+'17]

C.C. : $\mathcal{L}_{b \rightarrow c \ell \nu}^{NP} \supset -\frac{2G_F}{\sqrt{2}} V_{cb} \left[ \epsilon^\ell \bar{c} \gamma_\rho P_L b \cdot \bar{\ell} \gamma_\rho (1 - \gamma_5) \nu_\ell \right] + h.c.$

[X.-Q. Li+'16, Alonso+'16, Celis+'17]
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\( \delta^\mu(\mu_b) \) and \( \epsilon^\tau(\mu_b) \) at the level of \( \sim \mathcal{O}(10\% - 20\%) \) of the SM, with very different meanings: SM loop vs. SM tree

New degrees of freedom at scales \( \Lambda_{NP} \sim \mathcal{O}(1 - 100) \) TeV
Correlation with other flavor sectors

Move to specific models to relate $B$- and $K$-decays

[Crivellin+'16, Bordone+'17]

Rare $s \rightarrow d\nu\nu$ transitions

- NA62/CERN: $K^\pm \rightarrow \pi^\pm \nu\bar{\nu}$
- KOTO/J-PARC: $K_L \rightarrow \pi^0 \nu\bar{\nu}$ (CP Violation)

Collecting data, announcements expected before 202X ($X = 0, 1, 2$)
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**HERE:** discuss what can be learned from these transitions in some specific NP contexts: leptoquarks (LQs)
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A few interesting model-building directions:

- Z' models \[\text{[Altmannshofer+'14, Kamenik+'17,…]}\]
- New fermions $\Psi$ and scalars $\Phi$ \[\text{[Gripaios+'15, Arnan+'15]}\]
- LQs: couplings to quarks and leptons $\Rightarrow$ effects in (semi-)leptonic decays \[\text{[Hiller+'14, Gripaios+'14, Becirevic+'15'16, M. Varzielas+'15, Fajfer+'15,…]}\]

More generally, difficult to accommodate both classes of LFUV anomalies, $R_K (\ast)$ and $R_D (\ast)$, simultaneously.
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More generally, **difficult** to accommodate both classes of LFUV anomalies, \( R_K(\ast) \) and \( R_D(\ast) \), simultaneously.
Leptoquark models

- **First LQs: matter unification**

  [Pati, Salam '70's; Georgi, Glashow '74,...]

  - Phenomenological approach: a single (or a set of) LQ for flavor phenomenology, e.g., lightest particle in a concrete extension
  - Spin-0 and spin-1 particle coupling to SM + $\nu$ d.o.f., gauge invariant, dim. = 4 operators:
    - $S_3$, $R_2$, $\tilde{R}_2$, $\tilde{S}_1$, $S_1$, $\bar{S}_1$
    - 6 scalar LQs, $U_3$, $V_2$, $\tilde{V}_2$, $\tilde{U}_1$, $U_1$, $\bar{U}_1$
  - Vector LQs: renormalizable model requires larger spectrum
Leptoquark models

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  - 6 **vector LQs**: $U_3, V_2, \tilde{V}_2, \tilde{U}_1, U_1, \tilde{U}_1$

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- Vector LQs: **renormalizable** model requires larger spectrum

[Leptoquark models](#)
# Structure of LQ contributions to neutral currents

**Measurements:** $R_K/R_{K}^{SM}$ and $R_{K^*}/R_{K^*}^{SM} < 1$

<table>
<thead>
<tr>
<th>LQs</th>
<th>Couplings of scalar LQs to SM fermions</th>
<th>@ tree-level $R_K/R_{K}^{SM}$, $R_{K^<em>}/R_{K^</em>}^{SM}$</th>
</tr>
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<tr>
<td>$S_3 = (\bar{3}, 3, 1/3)$</td>
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<td>$&lt; 1, &lt; 1$</td>
</tr>
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<td>$R_2 = (3, 2, 7/6)$</td>
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<td>$\tilde{S}_1 = (\bar{3}, 1, 4/3)$</td>
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(w/ SM + $\nu_R$, also $\tilde{S}_1 = (\bar{3}, 1, -2/3)$ and new couplings)

→ Tree-level: $S_3$

→ Loop-level: other LQs can also imply $R_K/R_{K}^{SM}$, $R_{K^*}/R_{K^*}^{SM} < 1$
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In the following, we consider and compare:

- a $R_2$ model ("Doublet model")
- a $S_3$ model ("Triplet model")

Detailed phenomenological studies available

Substantial differences: e.g., $b \rightarrow s\ell\ell$ at different orders
**R₂ model: features**

Interactions with SM fermions:

\[
\mathcal{L}_{R_2}^Y = (Vg_R)_{ij} \bar{u}^i P_R e^j R_2^{5/3} + (g_R)_{ij} \bar{d}^i P_R e^j R_2^{2/3} + (g_L)_{ij} \bar{u}^i P_L \nu^j R_2^{2/3} - (g_L)_{ij} \bar{u}^i P_L e^j R_2^{5/3} + \text{h.c.}
\]

\[
g_R = 0_{3 \times 3}, \quad g_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & g_L^{c\mu} & g_L^{cT} \\ 0 & g_L^{t\mu} & g_L^{tT} \end{pmatrix}, \quad m_{R_2}
\]

- Avoid tree-level contributions to B-decays w/ the wrong chirality
- \(R_D(*)\) not addressed (e.g., \(g_R^{b\tau} \neq 0\) strongly constrained)
- Consistently avoid first generation couplings
- **No tree-level** contribution to \(s \to d\nu\nu\)
$R_2$ model: phenomenology

- $g_L^{c\tau} \approx 0$, $g_L^{t\tau} \approx 0$ for large $g_L^{c\mu}$, $g_L^{t\mu}$ due to $\tau \rightarrow \mu\gamma$

- $(g - 2)_\mu$ worsen by $\sim 1\sigma$

- Collider bounds: $m_{R_2} \gtrsim 650$ GeV (assuming $t\nu$, $t\tau$ dominate)
**S₃ model: features**

Interactions with SM fermions:

\[
\mathcal{L}^{S_3} \equiv -y_{ij} \bar{d}_L^C i \nu_L S_3^{1/3} - (V_{CKM}^* y)_{ij} \bar{u}_L C_{L i} \nu_{L j} S_3^{1/3} \\
- \sqrt{2} y_{ij} \bar{d}_L^C e^C_{L i} S_3^{4/3} + \sqrt{2} (V_{CKM}^* y)_{ij} \bar{u}_L C_{L i} \nu_{L j} S_3^{-2/3} + \text{h.c.}
\]

\[
y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{s\mu} & y_{s\tau} \\ 0 & y_{b\mu} & y_{b\tau} \end{pmatrix}, \quad V_{CKM}^* y \approx \begin{pmatrix} 0 & \lambda_{CKM} y_{s\mu} & \lambda_{CKM} y_{s\tau} \\ 0 & y_{s\mu} & y_{s\tau} \\ 0 & y_{b\mu} & y_{b\tau} \end{pmatrix}, \quad m_{S_3}
\]

- Single coupling matrix for up- and down-type processes
- With the choice \( y_{d\mu} = 0 \) ⇒ no \( s \rightarrow d\nu\nu \) @ tree-level
$S_3$ model: phenomenology

$R_{D^{(*)}}^{\mu/e} = \frac{B(B \to D^{(*)}\mu\nu)}{B(B \to D^{(*)}e\nu)}, \quad R_{\nu\nu}^{(*)} = \frac{B(B \to K^{(*)}\nu\nu)}{B(B \to K^{(*)}\nu\nu)_{SM}}, \quad \Delta m_s (B_s^0 \bar{B}_s^0)$

Collider bounds on LQ pair and $\tau\tau$ production satisfied

[Dörner+ '17]
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Overview

**Experimental values**

\[ \mathcal{B}_{\text{exp}}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 3.35 \times 10^{-10} \ @ 90 \% \text{ CL} \]  
[BNL-E787, E949]

\[ \mathcal{B}_{\text{exp}}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 2.6 \times 10^{-8} \ @ 90 \% \text{ CL} \]  
[KEK-E391a]

NA62 and KOTO: anticipated accuracies of 10%

**Theoretical predictions in the SM**

\[ \mathcal{B}_{\text{SM}}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 0.882^{+0.092}_{-0.098} \times 10^{-10} \ (\sim 10\%) \]  
[CKMfitter, preliminary]

\[ \mathcal{B}_{\text{SM}}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = 0.314^{+0.017}_{-0.018} \times 10^{-10} \ (\sim 5\%) \]  
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(tree- and loop-level observables used in the extraction of \( V_{CKM} \))

\[(sd)(ll)\) transitions in the SM: large \( B(K^\pm \rightarrow \pi^\pm \ell^+ \ell^-) \) points to large long-distance effects from \( K \rightarrow \pi \gamma^* \)
Results for the $R_2$ model

Max. enhancement of 9% for $K^\pm \rightarrow \pi^\pm \nu\nu$ and 5% for $K_L \rightarrow \pi^0 \nu\nu$

Effects induced by muon couplings, $g_L^{c\mu}$, $g_L^{t\mu}$
Preliminary results for the $S_3$ model

$\sim$ max. suppression of 10% for $K^\pm \rightarrow \pi^\pm \nu \nu$ and 14% for $K_L \rightarrow \pi^0 \nu \nu$

tau couplings:

$y_{d\tau} = [(1.9 + 0.7i)y_{b\tau} - (0.08 + 0.03i)y_{s\tau}] \times 10^{-4}$

S$_3$ model @ 1 TeV

Preliminary: sub-region of $\{g_{s\mu}, g_{b\mu}, g_{s\tau}, g_{b\tau}\}_{1\sigma}$
What do we learn?

To correlate $B$- and $K$-physics, two LQ models w/ real couplings:

$R_2 : \{ g_{L}^{c\mu}, g_{L}^{t\mu}, g_{L}^{c\tau}, g_{L}^{t\tau} \}, \quad S_3 : \{ y_{c\mu}, y_{t\mu}, y_{c\tau}, y_{t\tau} \}$ \quad ($m_{R_2} = m_{S_3} = 1$ TeV)

- Given a model: must rely on the **complementarity** of the two channels
- The comparison of $R_2$ and $S_3$ illustrates possible ways to **discriminate** models addressing the $B$-anomalies:
  - e.g., suppression/enhancements of $s \to d\nu\nu$
- **Important modulations** ($\gtrsim$ theo. unc.) also for $S_1 + S_3$:
  - suppression of $\sim 24\%$ for $K^\pm \to \pi^\pm \nu\nu$, $\sim 34\%$ for $K_L \to \pi^0 \nu\nu$

[Crivellin+’17]
Important exp. progress in the coming years in $K$-physics

- The specific correlation among $B$- and $K$-physics depends on a specific NP model

- LQ models: tentative class of extensions of the SM for interpreting the $b \rightarrow s \ell \ell$ anomalies

- The complementary study of $s \rightarrow d \nu \nu$ decays may favor a specific LQ models
Thanks!
### Couplings of scalar LQs to SM fermions

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Appendix

Results for the $S_3$ model + $y_{d\mu}$

- Relax the initial requirement of $y_{d\mu} = 0$
- A real $y_{d\mu}^{\text{tree}}$ saturates the experimental bound of $K^{\pm} \rightarrow \pi^{\pm} \nu\nu$: $|y_{d\mu}|$ below $\sim 3 \times 10^{-4}$
- Much stronger than $\tau \rightarrow \mu + K_S^0$

\[ y = \begin{pmatrix} 0 & y_{d\mu} & 0 \\ 0 & y_{s\mu} & y_{s\tau} \\ 0 & y_{b\mu} & y_{b\tau} \end{pmatrix} \]

[Davidson+'10]