Addressing $R_K$ and neutrino mixing in a class of $U(1)_X$ models

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Experimental anomalies and Global fits interpretation

\( b \to s\ell\ell \) anomalies at LHCb:

\[
R_K = \frac{\mathcal{BR}(B^+ \to K^+ \mu\mu)}{\mathcal{BR}(B^+ \to K^+ ee)} = 0.745^{+0.090}_{-0.074} \pm 0.036 \text{ for } q^2 \in [1, 6] \text{GeV}^2.
\]

SM prediction: \( 1 \pm 0.001 \Rightarrow \text{Lepton flavour non-universality} \)

- \( P'_5 \) for \( B \to K^*\mu\mu \)

Global fits: Simultaneous explanation if NP in **vector-axial** operators

\[
\begin{align*}
\mathcal{O}_9^\ell &= \bar{b}\gamma_\mu P_L s \bar{\ell}\gamma^\mu \ell, \\
\mathcal{O}_{10}^\ell &= \bar{b}\gamma_\mu P_L s \bar{\ell}\gamma^\mu \gamma_5 \ell, \\
\mathcal{O}'_9^\ell &= \bar{b}\gamma_\mu P_R s \bar{\ell}\gamma^\mu \ell, \\
\mathcal{O}'_{10}^\ell &= \bar{b}\gamma_\mu P_R s \bar{\ell}\gamma^\mu \gamma_5 \ell.
\end{align*}
\]
Global fits continued ...


2-D global fits in \((C_{9}^{NP,\mu}, C_{9}^{NP,e})\), \((C_{9}^{NP,\mu}, C_{10}^{NP,\mu})\) and \((C_{9}^{NP,\mu}, C'_{\mu})\)

\[ \chi^2 \text{ for } (C_{9}^{NP,\mu}, C_{9}^{NP,e}) \text{ better} \]
\[ C_{9}^{NP,e} \neq 0 \text{ allowed within } 2\sigma \]
Model building by taking RK anomaly at face value

- Introduce NP in $\mathcal{O}_9^\mu$ and $\mathcal{O}_9^e$ using $Z'$ of a $U(1)_X$ symmetry.
  - $R_K \Rightarrow$ diff $X$-charges for $e$ and $\mu$
  - dominant $Z'$ effects $\Rightarrow$ unequal $X$-charges for $d$-type quarks.

- Explain neutrino-mixings simultaneously with flavour $b \rightarrow s$ anomalies.

- $X$-charges of SM fermions:

<table>
<thead>
<tr>
<th>Quarks</th>
<th>$Q_1$</th>
<th>$u_R$</th>
<th>$d_R$</th>
<th>$Q_2$</th>
<th>$c_R$</th>
<th>$s_R$</th>
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<tr>
<th>Leptons</th>
<th>$L_1$</th>
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<th>$\mu_R$</th>
<th>$L_3$</th>
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- $X$-charge of $\Phi_{SM} = a\Phi_{SM}$
Model building by taking RK anomaly at face value continued ...

- $X$-charges are determined in a **bottom-up** approach (the importance stated in Camalich's talk) using constraints from:
  - Anomaly free $U(1)_X$.
  - $K - \bar{K}$.
  - $V_{ckm}$.
  - Global fits: Vanishing of $C_{9,10}^{\prime,\ell}$, $C_{10}^{NP,\ell}$.
  - $m_A$.
  - Allowed neutrino textures.
Constructing the $U(1)_X$ Model

- Introducing 3 $\nu_R$ + assigning vector-like charges, i.e.
  \[ x_{1L} = x_{1uR} = x_{1dR} = x_1 \]
  \[ \Rightarrow \text{anomaly free } U(1)_X, \]
  \[ \Rightarrow X \text{ charge of } \Phi_{\text{SM}} \text{ zero}, \]
  \[ \Rightarrow C_{10}^{\text{NP}, \ell} = 0. \]

- Equal $X$-charge of first two generation, i.e. $x_1 = x_2$
  \[ \Rightarrow \text{relaxed } K\bar{K} \text{ constraint} \]
  \[ \text{but } V_{\text{ckm}} \text{ in 1-2 sector: solved by adding } \Phi_{\text{NP}} \text{ with } X\text{-charge, } x_1 = x_3. \]

- $V_{dR} \approx 1 \Rightarrow C_{9,10}^{\text{NP}, \ell} = 0$ : achieved with $\Phi_{\text{NP}}$

- Introduce scalar singlet, $S$, charged under $U(1)_X$
  \[ \Rightarrow \text{masses to } Z', \nu_R\text{'s} \]
  \[ \Rightarrow \text{generates } U_{\text{PMNS}} \]
  \[ \Rightarrow \text{prevents } m_A \neq 0. \]
Introducing 3 $\nu_R$ + assigning vector-like charges, i.e.

$$x_{1L} = x_{1uR} = x_{1dR} = x_1$$

- $\Rightarrow$ anomaly free $U(1)_X$,
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- $\Rightarrow$ relaxed $K-K$ constraint
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$$V_{dR} \approx 1 \Rightarrow C_{9,10}^{NP,\ell} = 0 : \text{achieved with } \Phi_{NP}$$

Introduce scalar singlet, $S$, charged under $U(1)_X$

- $\Rightarrow$ masses to $Z'$, $\nu_R$'s
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Constructing the $U(1)_X$ Model continued ...

Selecting neutrino textures in accordance with global fit

- Plot:
  - allowed symmetries in lepton sector with atmost two-zeros in $M_R$
  - + Global fit contours in $(C^\mu_9, C^e_9)$

- Select: pass $1\sigma + C^\text{NP}, e, \mu \neq 0$.

- Selected combinations (6):
  - Type-A = $Le - 3L_\mu \pm L_\tau$.
  - Type-B = $Le - L_\mu \pm 3L_\tau$,
    - $Le - L_\mu \pm L_\tau$.

- Determine $X$-charges of quarks using $U(1)_X$ anomaly condition

\textbf{Figure: } $\tau$ charge suppressed.
Constructing the $U(1)_X$ Model continued ...

Selecting neutrino textures in accordance with global fit

- Plot:
  - allowed symmetries in lepton sector with atmost two-zeros in $M_R$
  - Global fit contours in $(C^\mu_9, C^e_9)$
- Select: pass $1\sigma + C^{NP, e, \mu}_9 \neq 0$.

Selected combinations (6):

- Type-A $= Le - 3L_\mu \pm L_\tau$.
- Type-B $= Le - L_\mu \pm 3L_\tau$, $Le - L_\mu \pm L_\tau$.

Determine $X$-charges of quarks using $U(1)_X$ anomaly condition

**Figure:** $\tau$ charge suppressed.
Combined flavour constraints from neutral meson mixings and global fits

Type-A: Allowed at 1σ overlap between $(B_s - \overline{B_s})$ and global fit: disregarded

Type-B: no 1σ overlap between $(B_s - \overline{B_s})$ and global fit: disregarded
Subjecting Type-A symmetries to direct production $Z'$ bounds from colliders

Collider bounds from: $\sigma(pp \rightarrow Z' \rightarrow \mu\mu)$

Bounds from flavour($B_s - \overline{B}_s$), global fit and collider: Substantial overlap
$R_K$ predictions for Type-A symmetries

Figure: $g_X = 0.2$
$Z'$ reach at the colliders for Type-A

Detection of $Z'$ in $\mu\mu$ channel:

![Diagram showing signal access over background for di-muon events](image1)

**Figure:** Schematic for signal access over background for di-muon events

![Significance for detecting $Z'$ with $g_X = 0.2$](image2)

**Figure:** Significance for detecting $Z'$ with $g_X = 0.2$
Summarizing

- Two symmetry combinations: $L_e - 3L_\mu \pm L_\tau$ pass all the constraints.

- Additional particles introduced: $Z'$, $\Phi_{NP}$, $S$ and 3 $\nu_R$'s.

- Possible to probe $L_e - 3L_\mu + L_\tau$ at 3$\sigma$ with $\sim 60$ fb$^{-1}$ luminosity: $M_{Z'} = 3800$ GeV and $g_X = 0.2$. 