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

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Experimental anomalies and Global fits interpretation

$b \rightarrow s\ell\ell$ anomalies at LHCb:

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

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

- $P'_{5}$ for $B \rightarrow K^*\mu\mu$

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

\[
\mathcal{O}_9^\ell = \bar{b}\gamma_\mu P_L s \bar{\ell} \gamma^\mu \ell, \quad \mathcal{O}_{10}^\ell = \bar{b}\gamma_\mu P_L s \bar{\ell} \gamma^\mu \gamma_5 \ell,
\]

\[
\mathcal{O}'_9^\ell = \bar{b}\gamma_\mu P_R s \bar{\ell} \gamma^\mu \ell, \quad \mathcal{O}'_{10}^\ell = \bar{b}\gamma_\mu P_R s \bar{\ell} \gamma^\mu \gamma_5 \ell.
\]
2-D global fits in \((C_{9}^{NP,\mu}, C_{9}^{NP,e})\), \((C_{9}^{NP,\mu}, C_{10}^{NP,\mu})\) and \((C_{9}^{NP,\mu}, C_{9}^{\prime,\mu})\)

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

- Introduce NP in $O_9^\mu$ and $O_9^e$ 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:

| Quarks     | $Q_1$ | $u_R$ | $d_R$ | $Q_2$ | $c_R$ | $s_R$ | $Q_3$ | $t_R$ | $b_R$ |
|------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| $U(1)_X$   | $x_{1L}$ | $x_{1uR}$ | $x_{1dR}$ | $x_{2L}$ | $x_{2cR}$ | $x_{2sR}$ | $x_{3L}$ | $x_{3tR}$ | $x_{3bR}$ |

| Leptons    | $L_1$ | $e_R$ | $L_2$ | $\mu_R$ | $L_3$ | $\tau_R$ |
|------------|-------|-------|-------|---------|-------|---------|
| $U(1)_X$   | $y_{1L}$ | $y_{1eR}$ | $y_{2L}$ | $y_{2\mu_R}$ | $y_{3L}$ | $y_{3\tau_R}$ |

- $X$-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 $U(1)_X$.
  - $K - \overline{K}$.
  - $V_{ckm}$.
  - Global fits: Vanishing of $C_{9,\ell}^{'}, C_{10,\ell}^{NP}$.
  - $m_A$.
  - Allowed neutrino textures.
Introducing 3 $\nu_R$ + assigning vector-like charges, i.e. $x_{1L} = x_{1uR} = x_{1dR} = x_1$

- $\Rightarrow$ anomaly free $U(1)_X$,
- $\Rightarrow$ $X$ charge of $\Phi_{SM}$ zero,
- $\Rightarrow C_{10}^\ell = 0$.

Equal $X$-charge of first two generation, i.e. $x_1 = x_2$

- $\Rightarrow$ relaxed $K$–$\bar{K}$ constraint
- but $V_{ckm}$ in 1-2 sector: solved by adding $\Phi_{NP}$ with $X$-charge, $x_1 - x_3$.

$V_{dR} \approx 1 \Rightarrow C'^{NP,\ell}_{9,10} = 0$: achieved with $\Phi_{NP}$

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

- $\Rightarrow$ masses to $Z'$, $\nu_R$'s
- $\Rightarrow$ generates $U_{PMNS}$
- $\Rightarrow$ prevents $m_A \neq 0$. 

| Fields | $Q_1$ | $Q_2$ | $Q_3$ | $L_1$ | $L_2$ | $L_3$ | $\Phi_{SM}$ | $\Phi_{NP}$ | $S$ |
|--------|-------|-------|-------|-------|-------|-------|-------------|------------|-----|
| $U(1)_X$ | $x_1$ | $x_2$ | $x_3$ | $x_1-uR$ | $x_1-dR$ | $x_1$ | $x_1-uR$ | $x_1-dR$ | $x_1$ |

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Constructing the $U(1)_X$ Model

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

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

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

- Introduce scalar singlet, $S$, charged under $U(1)_X$
  - $\Rightarrow$ masses to $Z'$, $\nu_R$'s
  - $\Rightarrow$ generates $U_{PMNS}$
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| Fields | $Q_1$ | $Q_2$ | $Q_3$ | $L_1$ | $L_2$ | $L_3$ | $\nu_R$ | $\Phi_{NP}$ | $S$ |
|--------|-------|-------|-------|-------|-------|-------|---------|------------|-----|
| $U(1)_X$ | $x_1$ | $x_1$ | $x_1$ | $x_1$ | $x_1$ | $x_1$ | $x_1$ | $x_1 - x_3$ | $K \rightarrow \bar{K}$ |
Constructing the $U(1)_X$ Model

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

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

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- Introduce scalar singlet, $S$, charged under $U(1)_X$
  - $\Rightarrow$ masses to $Z'$, $\nu_R$'s
  - $\Rightarrow$ generates $U_{PMNS}$
  - $\Rightarrow$ prevents $m_A \neq 0$. 

- Fields $Q_1$, $Q_2$, $Q_3$, $L_1$, $L_2$, $L_3$, $\nu_{SM}$, $\Phi_{NP}$, $S$
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. $x_1 = x_2$
  \[ \Rightarrow \text{relaxed } K \rightarrow \bar{K} \text{ constraint} \]
  \[ \text{but } V_{c_{km}} \text{ in 1-2 sector: solved by adding } \Phi_{\text{NP}} \text{ with } X \text{-charge, } x_1 - x_3. \]
  \[ V_{dR} \approx 1 \Rightarrow C_{9,10}^{\text{NP}, \ell} = 0 : \text{achieved with } \Phi_{\text{NP}} \]

- Introduce scalar singlet, $S$, charged under $U(1)_X$
  \[ \Rightarrow \text{masses to } Z', \nu_R's \]
  \[ \Rightarrow \text{generates } U_{\text{PMNS}} \]
  \[ \Rightarrow \text{prevents } m_A \neq 0. \]

| Fields | $Q_1$ | $Q_2$ | $Q_3$ | $L_1$ | $L_2$ | $L_3$ | $\Phi_{\text{SM}}$ | $\Phi_{\text{NP}}$ | $S$ |
|--------|------|------|------|------|------|------|---------------|----------------|-----|
| $U(1)_X$ | $x_1$ | $x_1$ | $x_3$ | $y_1$ | $y_2$ | $y_3$ | 0 | $x_1 - x_3$ | $x_1 - x_3$ |
Constructing the $U(1)_X$ Model

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

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

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

- Introduce scalar singlet, $S$, charged under $U(1)_X$
  - $\Rightarrow$ masses to $Z'$, $\nu_R$'s
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| Fields          | $Q_1$ | $Q_2$ | $Q_3$ | $L_1$ | $L_2$ | $L_3$ | $\Phi_{SM}$ | $\Phi_{NP}$ | $S$ |
|-----------------|-------|-------|-------|-------|-------|-------|--------------|-------------|-----|
| $U(1)_X$        | $x_1$ | $x_1$ | $x_3$ | $y_1$ | $y_2$ | $y_3$ | 0            | $x_1 - x_3$ | $x_1 - x_3$ |
Plot:
allowed symmetries in lepton sector with at most two-zeros in $M_R$ (in presence of $S$)
+ Global fit contours in $(C_9^\mu, C_9^e)$

Select: pass $1\sigma + C_9^{NP,e,\mu} \neq 0$.

Selected combinations (6):

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

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

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 $M_R$
  (in presence of $S$)
  + 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   | Allowed at 1σ | Disallowed at 1σ |
|--------|---------------|------------------|
| A      | 0.10 0.15 0.20 0.25 0.30 0.35 |
| B      | 0.10 0.15 0.20 0.25 0.30 0.35 |

$M_{Z'} (GeV)$ vs $g_X$

**Type-A**
- Accepted

**Type-B**
- Disallowed at 1σ

- $B_s - \overline{B_s}$
- Global fit
- 2σ reach

**Type-B**: no 1σ overlap between $(B_s - \overline{B_s})$ and global fit: disregarded

**Type-A**: Accepted
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: $g_X = 0.2$
Detection of $Z'$ in $\mu\mu$ channel:

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

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 $g_X = 0.2$. 