Implications of recent Flavour Anomalies on New Physics

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Outline

1. Introduction
2. Status of Flavour Anomalies
   - $b \rightarrow c \ell \bar{\nu}_\ell$
   - $b \rightarrow s \ell^+ \ell^-$
   - Cabibbo Angle Anomaly: $R(V_{us}) \sim 3\sigma$
3. Explanation of the Anomalies in EFT approach
4. Common Explanation with specific NP Models
5. Conclusion
Motivation

- No direct evidence of NP either in Energy frontier or Intensity frontier
- There are a few open issues, which can not be addressed in the SM
  - Existence of Dark Matter $\Rightarrow$ New weakly interacting particles
  - Non-zero neutrino masses $\Rightarrow$ Right-handed (sterile) neutrinos
  - Observed Baryon Asymmetry of the Universe $\Rightarrow$ Additional CP violating interactions
- SM must be extended. What is the underlying fundamental theory?

Need to explore all the three frontiers:
- Cosmic Frontier
- Energy Frontier
- Intensity Frontier
Flavour observables are quite sensitive to high energy scales through virtual effects.

At colliders large no of (thousands of millions) heavy quarks/leptons are produced and their decays into light flavours are measured.

Confronting the expt. results with SM predictions (if some mismatch is found), would provide hints for NP.

Flavour Physics can probe NP at much higher scale than the direct searches at Colliders.
In the SM, the couplings of the gauge bosons to leptons are independent of the lepton flavour.

Equal couplings of the $W$ and $Z$ bosons to electrons, muons and taus.

Yukawa sector breaks the universality in two ways $\mathcal{L}_{SM} \supset Y_{ij}^{E} \overline{L}_i E_R^j H + \text{h.c.}$

In the mass terms $m_e \neq m_\mu \neq m_\tau$ and in Higgs interactions (negligible for flavour physics).

LFU is enforced in the SM by construction and any violation of it would be a clear sign of physics beyond the SM.

Over the years, LFU violation has been searched in several other systems $(Z \rightarrow \ell\ell, W \rightarrow \ell\nu, J/\psi \rightarrow \ell\ell, \pi \rightarrow \ell\nu, K \rightarrow (\pi)\ell\nu, \cdots)$.

These measurements provide very strong limit on lepton non-universality in the EW sector.
Quick Recap of Recent Anomalies in B-sector

- However, in last few years there are several measurements, which do not agree with the SM predictions.

- These deviations are not statistically significant enough to claim the discovery of NP. At the same time, they are not weak enough to be completely ignored.

- They may be considered as smoking-gun signals of possible NP.

- Some of these are:
  - $R_{D(*)}$ Anomaly ($b \rightarrow c\ell\nu$): NP in charged currents
  - $R_{K(*)}$ Anomaly (Hint for Lepton Flavour Non-Universality)
  - Deviations in $b \rightarrow s\mu\mu$: $P_5'$, $BR(B \rightarrow K^{(*)}\mu\mu)$, $B_s \rightarrow \phi\mu\mu$ (NP in FCNC transitions)

- These anomalies may guide us how to probe or go beyond the SM
Recent anomalies in the $B$ sector

1. $R_{D(*)}$

$$R_{D(*)} = \frac{\text{Br}(\bar{B} \rightarrow D(\ast) \tau \bar{\nu}_\tau)}{\text{Br}(\bar{B} \rightarrow D(\ast) \ell \bar{\nu}_\ell)},$$

$$R_{D(*)}^{\text{Expt}} > R_{D(*)}^{\text{SM}}$$

$$R_D^{\text{Expt}} = 0.340 \pm 0.027 \pm 0.013, \quad R_D^{\text{Expt}} = 0.295 \pm 0.011 \pm 0.008$$

$$R_D^{\text{SM}} = 0.299 \pm 0.003, \quad R_D^{\text{SM}} = 0.258 \pm 0.005.$$  

3.08σ discrepancy between Expt and SM results.
Summary of $R_D$ & $R_{D^*}$ from various Measurements
About $3\sigma$ deviation from SM prediction, seen in 3 different expts with different tagging methods (hadronic and semileptonic).

Measurements are consistent with $e/\mu$ universality $R_D^{\text{Exp}} = 0.995(45)$, $R_{D^*}^{\text{Exp}} = 1.04(5)$

In addition Belle also has measured

$$P_{\tau}^{D^*} |_{\text{Exp}} = -0.38 \pm 0.51^{+0.21}_{-0.16}, \quad \text{(SM : } -0.497 \pm 0.01)$$

$$F_L^{D^*} |_{\text{Exp}} = 0.60 \pm 0.08 \pm 0.04, \quad \text{(SM : } 0.46 \pm 0.04) \quad \text{(1.6}\sigma\text{ discrepancy)}$$

LHCb result on $R_{J/\psi}$

$$R_{J/\psi} = \frac{BR(B_c \to J/\psi\tau\nu)}{BR(B_c \to J/\psi\mu\nu)} = 0.71 \pm 0.17 \pm 0.18$$

has about $2\sigma$ deviation from its SM value $R_{J/\psi} = 0.283 \pm 0.048$.

10% enhancement of the tau SM amplitude $\Rightarrow$ LUV in $b \to c\tau\nu$ as

$$\Lambda \simeq 3 \text{ TeV (Tree level NP)} \quad \frac{V_{cb}}{v^2} \overset{\text{vs.}}{\sim} \frac{1}{\Lambda^2}$$
Sizable discrepancies ($> 2\sigma$) reported by the LHCb and Belle Collaborations in the ratio $R_{K^(*)}$

$$R_{K^(*)} = \frac{\text{Br}(B \rightarrow K^(*) \mu\mu)}{\text{Br}(B \rightarrow K^(*) ee)}$$

$LNU$ observable & SM prediction & Expt. value & Deviation  

$R_K \mid q^2 \in [1.0, 6.0]$ & $1.0003 \pm 0.0001$ & $0.846^{+0.060,+0.016}_{-0.054,-0.014}$ (LHCb) $1.03^{+0.28+0.28}_{-0.24-0.24} \pm 0.01$ (Belle : $R_{K^+} + R_{K_S}$) & $2.5\sigma$  

$R_{K^*} \mid q^2 \in [0.045, 1.1]$ & $0.92 \pm 0.02$ & $0.660^{+0.110}_{-0.070} \pm 0.024$ (LHCb) $0.52^{+0.36}_{-0.26} \pm 0.05$ (Belle) & $2.2\sigma$  

$R_{K^*} \mid q^2 \in [1.1, 6.0]$ & $1.00 \pm 0.01$ & $0.685^{+0.113}_{-0.007} \pm 0.047$ (LHCb) $0.96^{+0.45}_{-0.29} \pm 0.11$ (Belle) & $2.4\sigma$
Dynamics for $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

The decay distribution of $B^0 \rightarrow K^{*0}(\rightarrow K\pi)\ell\ell$ described by 3 angles ($\theta_l, \theta_K, \phi$) and $q^2$

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\Omega} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K ight.$$

$$+ \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_l - F_L \cos^2 \theta_K \cos 2\theta_l$$

$$+ S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi$$

$$+ S_5 \sin 2\theta_K \sin \theta_l \cos \phi + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_l$$

$$+ S_7 \sin 2\theta_K \sin \theta_l \sin \phi + S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi$$

$$+ S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \left] \right.$$}

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1 - F_L)}}, \quad P'_6 = \frac{S_7}{\sqrt{F_L(1 - F_L)}}$$

$$\tilde{\Omega} = (\cos \theta_l, \cos \theta_K, \phi)$$
FFI observables in $B \rightarrow K^{*\ell\ell}$

$P'_{4,5}$

LHCb: PRL 125, 011802 (2020)

ATLAS Results show
~ 2.7σ deviation
\( Q_{4,5} \)

\[ Q_i = P_i^{\mu} - P_i^e \]

Belle: PRL 118, 111801 (2017)

- Considering 20\% deficit in SM muon channel \( \Rightarrow \) LUV in \( b \to s\ell\ell \)

\[ \Lambda \simeq 30 \text{ TeV} \text{ (Tree level NP)} \]

\[ \Lambda \simeq 3 \text{ TeV} \text{ (One – loop NP)} \]
\[ R_{pK} : \Lambda_b \to \Lambda(1520)\ell^+\ell^- \]

\[ R_{pK}^{-1} = \frac{\mathcal{B}(\Lambda_b^0 \to pK^- e^+ e^-)}{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi(\to e^+ e^-))} \bigg/ \frac{\mathcal{B}(\Lambda_b^0 \to pK^- \mu^+ \mu^-)}{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+ \mu^-))}. \]

\[ R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05 \quad \text{Consistent with SM} \quad \text{JHEP 40 (2020)} \]
The rare decay $B_s \rightarrow \mu^+ \mu^-$ is mediated through quark level transition $b \rightarrow s \mu \mu$ and occur at 1-loop level in the SM

$$\text{Br}(B_s \rightarrow \mu \mu) = \left(2.69^{+0.37}_{-0.35}\right) \times 10^{-9}$$

$$\text{Br}(B_d \rightarrow \mu \mu) < 1.6 \times 10^{-10} \ (90\% \ \text{CL})$$

$$\text{Br}(B_s \rightarrow \mu \mu)|_{SM} = (3.66 \pm 0.14) \times 10^{-9}$$

$$\text{Br}(B_d \rightarrow \mu \mu)|_{SM} = (1.03 \pm 0.05) \times 10^{-10}$$

$\text{Br}(B_s \rightarrow \mu \mu)$ has $2.4\sigma$ discrepancy with SM
### Summary of Observed Anomalies in $b$ decays

<table>
<thead>
<tr>
<th>Decay Processes</th>
<th>$b \rightarrow c \ell \bar{\nu}_\ell$</th>
<th>$b \rightarrow s \ell^+ \ell^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Observables</strong></td>
<td>$R_D, R_{D^<em>}, R_{J/\psi}, F_L^{D^</em>}, P_\tau^{D^*}$</td>
<td>$R_K, R_{K^*}, P_5^I, B$</td>
</tr>
<tr>
<td><strong>SM</strong></td>
<td>Tree level</td>
<td>One-loop (FCNC process)</td>
</tr>
<tr>
<td></td>
<td>CKM favored</td>
<td>GIM suppressed</td>
</tr>
<tr>
<td><strong>LFU violation</strong></td>
<td>$\tau$ vs. $e/\mu$</td>
<td>$\mu$ vs. $e$</td>
</tr>
<tr>
<td><strong>Caveats</strong></td>
<td>$\tau$ reconstruction difficult</td>
<td>$e$ reconstruction difficult at LHCb</td>
</tr>
<tr>
<td><strong>Advantages</strong></td>
<td>Well-understood theory</td>
<td>Solid theory for $R_{K^*(\ast)}$, Some caveats for $P_5^I$ and $B$</td>
</tr>
</tbody>
</table>

- Lots of reasons to be excited!
  - **Two different sets of anomalies of very different taste**
- All combined, the most compelling hints for physics BSM seen so far.
Cabibbo Angle Anomaly: 1912.08823

- $V_{us}$ extracted from $\tau$ decays and $K$ decays do not perfectly agree.
- There is $\sim (3 - 4)\sigma$ tension between these determinations and the one from $V_{ud}$ from super-allowed decay

Can be explained by LFU violating NP in neutrino sector

$$-i \frac{g^2}{\sqrt{2}} \bar{\ell}_i \gamma^\mu P_L \nu_j W_\mu$$

$$\Rightarrow -i \frac{g^2}{\sqrt{2}} \bar{\ell}_i \gamma^\mu P_L \nu_j W_\mu \left( \delta_{ij} + \frac{1}{2} \varepsilon_{ij} \right)$$

$$-i \frac{g^2}{\sqrt{2}c_W} \bar{\nu}_i \gamma^\mu P_L \nu_j Z_\mu \Rightarrow -i \frac{g^2}{\sqrt{2}c_W} \bar{\nu}_i \gamma^\mu P_L \nu_j Z_\mu \left( \delta_{ij} + \frac{1}{2} \varepsilon_{ij} \right)$$

CMS: 1907.06737, SGPR: 1807.10197
Nonzero $\varepsilon_{ee}$ and $\varepsilon_{\mu\mu}$ are preferred at 99% CL.
How to address the Anomalies in $b$ sector

- As seen, the NP scales are quite different for the CC $b \rightarrow c \ell \nu$ and NC $b \rightarrow s \ell \ell$ transitions if the effect of NP is considered at tree level for both the processes. So tree level contribution with single mediator like $W'$ for $b \rightarrow c$ and $Z'$ for $b \rightarrow s$ will not work.

- However, if NP contributions arise at tree level for CC and at loop-level for NC, then the scale could be same for both processes

- **First step:** To construct effective Lagrangian which might explain experimental data

- **Next, to find the new particles which can mimic effective Lagrangian**

- **Need to check all other low energy flavour constraints, electroweak observables, including direct searches for NP at LHC**

- **Construct the consistent model for NP of your choice!**
Effective Field Theory Approach for $b \rightarrow c\tau^{-}\bar{\nu}_{\tau}$

- Most of the EFT analyses assume that NP is present mainly in $b \rightarrow c\tau^{-}\bar{\nu}_{\tau}$ transitions
- As there are no signs of LU violation, for electron and muon in $b \rightarrow c\ell\bar{\nu}_{\ell}$ decays

\[
R_{D}^{\mu/e} = \frac{Br(B \rightarrow D_{\mu\nu})}{Br(B \rightarrow D_{\ell\nu})} = 0.995(45)
\]
\[
R_{D^*}^{\mu/e} = \frac{Br(B \rightarrow D^*_{\mu\nu})}{Br(B \rightarrow D^*_{\ell\nu})} = 1.04(5)
\]
EFT for $b \rightarrow c \tau^{-} \bar{\nu}_{\tau}$

NP contributions to $b \rightarrow c \tau \nu$ (over complete set of operators)\(^{(1506.08896)}\)

$$\mathcal{H} = \frac{4G_F}{\sqrt{2}} V_{cb} \mathcal{O}_{V_L} + \frac{1}{\Lambda^2} \sum_i C_i^{(i,i')} \mathcal{O}_i^{(i,i')}$$

<table>
<thead>
<tr>
<th>Operator</th>
<th>Fierz identity</th>
<th>Allowed Current</th>
<th>$\delta \mathcal{L}_{\text{int}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{O}_{V_L}$</td>
<td>$(\bar{c}\gamma_{\mu}P_Lb)(\bar{\tau}\gamma_{\mu}P_L\nu)$</td>
<td>$O_{V_L}$</td>
<td>$(1,3)_0$</td>
</tr>
<tr>
<td>$\mathcal{O}_{V_R}$</td>
<td>$(\bar{c}\gamma_{\mu}P_Rb)(\bar{\tau}\gamma_{\mu}P_L\nu)$</td>
<td>$-2O_{SR}$</td>
<td>$(3,3)_{2/3}$</td>
</tr>
<tr>
<td>$\mathcal{O}_{S_R}$</td>
<td>$(\bar{c}P_Rb)(\bar{\tau}P_L\nu)$</td>
<td>$-\frac{1}{2}O_{V_R}$</td>
<td>$(3,1)_{2/3}$</td>
</tr>
<tr>
<td>$\mathcal{O}_{S_L}$</td>
<td>$(\bar{c}P_Lb)(\bar{\tau}P_L\nu)$</td>
<td>$-\frac{1}{2}O_{S_L} - \frac{1}{8}O_T$</td>
<td>$(3,2)_{7/6}$</td>
</tr>
<tr>
<td>$\mathcal{O}_{T}$</td>
<td>$(\bar{c}\sigma_{\mu\nu}P_Lb)(\bar{\tau}\gamma_{\mu\nu}P_L\nu)$</td>
<td>$-6O_{S_L} + \frac{1}{2}O_T$</td>
<td>$(3,3)_{1/3}$</td>
</tr>
<tr>
<td>$\mathcal{O}_{V_L}''$</td>
<td>$(\bar{c}\gamma_{\mu}P_CC^c)(\bar{\tau}\gamma_{\mu}P_C\nu)$</td>
<td>$-O_{V_R}$</td>
<td>$\left(\bar{3},1\right)_{3/3}$</td>
</tr>
<tr>
<td>$\mathcal{O}_{V_R}''$</td>
<td>$(\bar{c}\gamma_{\mu}P_RC^c)(\bar{\tau}\gamma_{\mu}P_C\nu)$</td>
<td>$-2O_{SR}$</td>
<td>$(3,2)_{5/3}$</td>
</tr>
<tr>
<td>$\mathcal{O}_{S_R}''$</td>
<td>$(\bar{c}P_RC^c)(\bar{\tau}\gamma_{\mu}P_C\nu)$</td>
<td>$\frac{1}{2}O_{V_L}$</td>
<td>$(3,3)_{1/3}$</td>
</tr>
<tr>
<td>$\mathcal{O}_{S_L}''$</td>
<td>$-\frac{1}{2}O_{S_L} + \frac{1}{8}O_T$</td>
<td>$(\bar{3},1)_{1/3}$</td>
<td>$(\bar{3},1)_{1/3}$</td>
</tr>
<tr>
<td>$\mathcal{O}_{T}''$</td>
<td>$-6O_{S_L} - \frac{1}{2}O_T$</td>
<td>$(\bar{3},1)_{1/3}$</td>
<td>$(\bar{3},1)_{1/3}$</td>
</tr>
</tbody>
</table>
Global Fit to NP Couplings

Global fits are performed by various groups including the measurements on $R_D$, $R_{D^*}$, $q^2$ deferential distribution, $F_L^{D^*}$, $\mathcal{B}(B_c \rightarrow \tau\nu)$.

In addition to global minima there are are also local minima.

<table>
<thead>
<tr>
<th>$\mathcal{B}(B_c \rightarrow \tau\nu)$</th>
<th>Min 1b</th>
<th>Min 2b</th>
<th>Min 1b</th>
<th>Min 2b</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\chi^2_{\text{min}}/\text{d.o.f.}$</td>
<td>37.6/54</td>
<td>42.1/54</td>
<td>37.6/54</td>
<td>42.0/54</td>
</tr>
<tr>
<td>$C_{VL}$</td>
<td>0.14$^{+0.14}_{-0.12}$</td>
<td>0.41$^{+0.05}_{-0.05}$</td>
<td>0.14$^{+0.14}_{-0.14}$</td>
<td>0.40$^{+0.06}_{-0.07}$</td>
</tr>
<tr>
<td>$C_{SR}$</td>
<td>0.09$^{+0.14}_{-0.52}$</td>
<td>$-1.15^{+0.18}_{-0.09}$</td>
<td>0.09$^{+0.33}_{-0.56}$</td>
<td>$-1.34^{+0.57}_{-0.08}$</td>
</tr>
<tr>
<td>$C_{SL}$</td>
<td>$-0.09^{+0.52}_{-0.11}$</td>
<td>$-0.34^{+0.13}_{-0.19}$</td>
<td>$-0.09^{+0.68}_{-0.21}$</td>
<td>$-0.18^{+0.13}_{-0.57}$</td>
</tr>
<tr>
<td>$C_T$</td>
<td>0.02$^{+0.05}_{-0.05}$</td>
<td>0.12$^{+0.04}_{-0.04}$</td>
<td>0.02$^{+0.05}_{-0.05}$</td>
<td>0.11$^{+0.03}_{-0.04}$</td>
</tr>
</tbody>
</table>

1904.09311
\( \mathcal{O}_{V_L} \) has the same Lorentz structure as SM hence \( R_D \) and \( R_{D^*} \) proportional to \((1 + C_{V_L})^2\): Preferred scenario

\( \mathcal{O}_{V_R} \): \( R_D \propto (1 + C_{V_R})^2 \) whereas \( R_{D^*} \propto (1 - C_{V_R})^2 \), hence not possible to find a common solution to both \( R_D \) and \( R_{D^*} \).

\( \mathcal{O}_{S_L} \) and \( \mathcal{O}_{S_R} \) predict large branching ratio for \( B_c \to \tau \nu \), hence constrained by \( B_c \) lifetime.

Large value of tensor operator predicts small \( F_L^{D^*} \) but provides a decent description to data. However, such operators not easily generated by NP theories at EW scale. In some cases they appear due to RG evolution from EW scale to \( b \) quark scale, with strong correlation with scalar operators.
Effective Field Theory Approach for $b \rightarrow s\ell\ell$

- Compared to $b \rightarrow c\ell\nu_\ell$, $b \rightarrow s\ell\ell$ transitions are richer due to large no of observables
- The effective Hamiltonian describing $b \rightarrow s\ell^+\ell^-$ process

$$
\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[ \sum_{i=1}^{6} C_i(\mu) O_i + \sum_{i=7,9,10,S,P} \left( C_i(\mu) O_i + C'_i(\mu) O'_i \right) \right].
$$

<table>
<thead>
<tr>
<th>1D Hyp.</th>
<th>All</th>
<th>LFUV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{9\mu}^{NP}$</td>
<td>-1.03</td>
<td>6.3</td>
</tr>
<tr>
<td>$C_{9\mu} = -C_{10\mu}^{NP}$</td>
<td>-0.50</td>
<td>5.8</td>
</tr>
<tr>
<td>$C_{9\mu}^{NP} = -C_{9\gamma\mu}$</td>
<td>-1.02</td>
<td>6.2</td>
</tr>
<tr>
<td>$C_{9\mu}^{NP} = -3C_{9e}^{NP}$</td>
<td>-0.93</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Best fit values for new WCs: 1903.09578
Grobal-fit Results (1D)
• Good fits obtained along the direction $C_{9\mu}^{NP} = -C_{10\mu}^{NP}$, arises naturally in models obeying $SU(2)_L$ invariance.

<table>
<thead>
<tr>
<th>2D Hyp.</th>
<th>All</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Best fit</td>
<td>$\text{Pull}_{\text{SM}}$</td>
</tr>
<tr>
<td>$(C_{9\mu}^{NP}, C_{10\mu}^{NP})$</td>
<td></td>
<td>(-0.98,+0.19)</td>
<td>6.2</td>
</tr>
<tr>
<td>$(C_{9\mu}^{NP}, C_{7'}^{NP})$</td>
<td></td>
<td>(-1.04,+0.01)</td>
<td>6.0</td>
</tr>
<tr>
<td>$(C_{9\mu}^{NP}, C_{9'}^{NP})$</td>
<td></td>
<td>(-1.14,+0.55)</td>
<td>6.5</td>
</tr>
<tr>
<td>$(C_{9\mu}^{NP}, C_{10'}^{NP})$</td>
<td></td>
<td>(-1.17,-0.33)</td>
<td>6.6</td>
</tr>
<tr>
<td>$(C_{9\mu}^{NP}, C_{9e}^{NP})$</td>
<td></td>
<td>(-1.09,-0.25)</td>
<td>6.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2D Hyp.</th>
<th>$C_{7}^{NP}$</th>
<th>$C_{9\mu}^{NP}$</th>
<th>$C_{10\mu}^{NP}$</th>
<th>$C_{7'}^{NP}$</th>
<th>$C_{9'}^{NP}$</th>
<th>$C_{10'}^{NP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best fit</td>
<td>+0.00</td>
<td>-1.13</td>
<td>+0.20</td>
<td>+0.00</td>
<td>+0.49</td>
<td>-0.10</td>
</tr>
<tr>
<td>1 $\sigma$</td>
<td>[-0.02, +0.02]</td>
<td>[-1.30, -0.96]</td>
<td>[+0.05, +0.37]</td>
<td>[-0.01, +0.02]</td>
<td>[+0.04, +0.95]</td>
<td>[-0.33, +0.14]</td>
</tr>
<tr>
<td>2 $\sigma$</td>
<td>[-0.03, +0.04]</td>
<td>[-1.46, -0.78]</td>
<td>[-0.09, +0.57]</td>
<td>[-0.03, +0.04]</td>
<td>[-0.39, +1.45]</td>
<td>[-0.55, +0.41]</td>
</tr>
</tbody>
</table>

fit values for new WCs: 1903.09578
Discriminating power of $R_K$ and $R_{K^*}$ ($\mu$ vs. $e$) 1704.05438

\[ \mathcal{H}_{\text{eff}} = -V_{tb}V_{ts}^* \frac{\alpha}{4\pi v^2} \sum_{\ell, X, Y} C_{bX} \ell Y (\bar{s} \gamma_{\mu} P_X b)(\bar{\ell} \gamma^{\mu} P_Y \ell) + \text{h.c} \]

\[ C_9 = C_{bL \mu_L + R} / 2, \quad C_{10} = -C_{bL \mu_L - R} / 2 \]
The EFT approach provides a framework to correlate the LU deviations in the tree- ($b \to c\tau\nu$) and loop-level $b \to s\ell\ell$ transitions. Since both LU deviations are well explained by a NP vector contribution to left-handed-fermions, it is natural to consider the general structure

$$\mathcal{L}_{NP} \propto \frac{\lambda^q_{ii} \lambda^\ell_{\alpha\beta}}{v^2} \left[ C_T(\bar{Q}_i L_{\gamma\mu}\sigma^a Q_j^i)(\bar{L}_\alpha L_{\gamma\mu}\sigma^a L_\beta^\beta) + C_S(\bar{Q}_i L_{\gamma\mu} Q_j^i)(\bar{L}_\alpha L_{\gamma\mu} L_\beta^\beta) \right]$$

$Q_L^i \sim (V_{ji}^* u_L^i, d_L)$ and $L_\alpha^\alpha = (\nu_\alpha^\alpha, \ell_\alpha^\alpha)$, $C_S$ and $C_T$ are singlet and triplet couplings w.r.t $SU(2)_L$.

In this framework, the same four-fermion operator $(\bar{Q}_L^i \gamma_\mu Q_L^i)(\bar{L}_\alpha L_{\gamma\mu} L_\beta^\beta)$ yields both FCNC and FCCC processes.
Using the identity $\sigma^a_{ij}\sigma^a_{kl} = 2\delta_{il}\delta_{kj} - \delta_{ij}\delta_{kl}$, the first operator can become

\[(\bar{Q}_L\gamma_\mu\sigma^aQ_L)(\bar{L}_L\gamma^\nu\sigma^aL_L) \sim 2(\bar{Q}_L^i\gamma_\mu\sigma^aQ_L^j)(\bar{L}_L^\alpha\gamma^\nu\sigma^aL_L^\beta) - (\bar{Q}_L\gamma_\mu\sigma^aQ_L)(\bar{L}_L\gamma^\nu\sigma^aL_L)\]

The two operators correspond to different underlying NP. First one: both CC and NC, second one: NC

The flavour structure is contained in the matrices $\lambda^q_{ij}$, $\lambda^\ell_{\alpha\beta}$.

Minimally broken Flavour symmetry $U(2)_q \times U(2)_\ell$ symmetry is assumed, which is defined as follows:

The first two generations of left-handed quarks and leptons transform as doublets under the corresponding $U(2)$ groups, while the third generation and all the right-handed fermions are singlets.

This symmetry is minimally broken by two spurions $V_q \sim (2, 1)$ and $V_\ell \sim (1, 2)$ which are conventionally chosen as $V_q \equiv (V_{td}^*, V_{ts}^*)$ and $V_\ell \equiv (0, V_{\tau\mu}^*)$ with $V_{\tau\mu} \ll 1$. 

Common Explanations
Common Explanations

- The effect in $R_{D^*}$ is correlated to $b \to s\ell\ell$ and/or $b \to s\nu\nu$ following the NP contributions $C_{9\mu}^{NP} = -C_{10\mu}^{NP}$.

- Since $b \to c\ell\nu$ processes are mediated by tree level in SM, a rather large NP contribution is required and in principle large contributions to $b \to s\nu\nu$ processes also appear.

- Bounds from $B \to K^*\nu\nu$ can be avoided by aligning the coupling structure mainly to the third generation.

- Constraints also come from LFV decays like $B \to K\mu\tau$.

- Flavour symmetries can be used to ensure the proper hierarchy of couplings to the other families and to avoid too large contributions to LFV processes like $U(2)_q \times U(2)_\ell$. 
Leptoquarks

Leptoquarks are color triplet bosons that couple to quarks and leptons:

<table>
<thead>
<tr>
<th>LQ</th>
<th>SM rep</th>
<th>Spin</th>
<th>$F=3B+S$</th>
<th>Proton decay</th>
<th>$R_{K(*)}$</th>
<th>$R_{D(*)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>$(3, 1, +1/3)$</td>
<td>0</td>
<td>$-2$</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>$\bar{S}_1$</td>
<td>$(3, 1, -2/3)$</td>
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<td>$-2$</td>
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<td>No</td>
<td>No</td>
</tr>
<tr>
<td>$\tilde{S}_1$</td>
<td>$(3, 1, +4/3)$</td>
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<td>$-2$</td>
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<td>No</td>
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<tr>
<td>$S_3$</td>
<td>$(\bar{3}, 3, +1/3)$</td>
<td>0</td>
<td>$-2$</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>$R_2$</td>
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<td>0</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>$\tilde{R}_2$</td>
<td>$(3, 2, +1/6)$</td>
<td>0</td>
<td>0</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>$U_1$</td>
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<td>0</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>$\bar{U}_1$</td>
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<td>1</td>
<td>0</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>$\tilde{U}_1$</td>
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<td>0</td>
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<td>No</td>
<td>No</td>
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<tr>
<td>$U_3$</td>
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<td>0</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>$V_2$</td>
<td>$(\bar{3}, 2, +5/6)$</td>
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<td>$-2$</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>$\tilde{V}_2$</td>
<td>$(\bar{3}, 2, -1/6)$</td>
<td>1</td>
<td>$-2$</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
Single Scalar Leptoquark $S_1(3, 1, -1/3) \equiv \phi$: 1511.01900

- Leptoquark can couple to $(L_L Q_L)$ and $e_R u_R$
- An additional discrete symmetry has to be imposed (with $L_L$ and $\phi$ have opposite parity) to avoid proton decay
- The interaction Lagrangian

$$\mathcal{L} \supset \bar{Q}^c \lambda^L i \tau_2 L \phi^* + \bar{u}^c_R \lambda^R e_R \phi^* + \text{H.c.} \quad \text{(weak basis)}$$

$$= \bar{u}^c_L \lambda^e_{\mu e} e_L \phi^* - \bar{d}^c_L \lambda^d_{
u \nu} \nu_L \phi^* + \bar{u}^c_R \lambda^e_{\mu e} e_R \phi^* + \text{H.c.} \quad \text{(mass basis)}$$

- $\phi$ mediates semileptonic B-meson decays at tree level

$$\mathcal{L}_{\text{eff}} = \frac{1}{2 M^2_\phi} \left[ - \lambda^L_{u_i l_j} \lambda^L_{b \nu_k} \bar{u}^i_L \gamma^\mu b_L \bar{\nu}^j_L \gamma^\mu \nu_k + \lambda^R_{u_i l_j} \lambda^L_{b \nu_k} \left( \bar{u}_R b_L \nu^j_R - \text{Tensor term} \right) \right]$$
For a TeV scale LQ, the fit to expt. data on $R_{D(*)}$ gives

$$\lambda_{c_T}^L \lambda_{b\nu\tau}^L \approx 0.35 \left( \frac{M_\phi}{1 \text{ TeV}} \right)^2, \quad \lambda_{c_T}^R \lambda_{b\nu\tau}^L \approx -0.03 \left( \frac{M_\phi}{1 \text{ TeV}} \right)^2.$$  

The model also gives tree level FCNC $B \to K\nu\nu$ and $D^0 \to \mu\mu$ (consistent with the present upper bound for suitable choice of couplings)

The $b \to s\mu\mu$ transition occurs at one-loop level:

$$C_{LL}^\mu = \frac{m_t^2}{8\pi\alpha M_\phi^2} \left| \lambda_t^L \right|^2 - \frac{1}{64\pi\alpha} \frac{\sqrt{2}}{G_F M_\phi^2} \left( \lambda_L \lambda_L^{L\dagger} \right)_{bs} (\lambda_L \lambda_L^{L\dagger})_{\mu\mu} \Rightarrow (-1.5 < C_{LL}^\mu < -0.7).$$

The model also explains $(g-2)_\mu$, and $\tau \to \mu\gamma$

Cons: Discrete symmetry is adhoc, Not UV complete, etc..
The Yukawa int. Lagrangian in this model

\[ \mathcal{L} = \bar{d}_R' \lambda_L (\tilde{\Delta})^\dagger L' + \bar{Q}_R' \lambda_R \Delta \nu_R' + \text{H.c.} \]  
(int. basis)

\[ = \bar{d}_R \lambda_L U_{PMNS} \nu L \Delta^{-1/3} - \bar{d}_R \lambda_L \ell L \Delta^{2/3} + \bar{u}_L V_{CKM} \lambda_R \nu R \Delta^{2/3} + \bar{d}_L \lambda_R \nu R \Delta^{-1/3} \]

The model also assumes a light RH \( \nu_R \)

- Both \( b \to c \ell \nu \) and \( b \to s \ell \ell \) occur at tree level
The $b \to s\mu\mu$ transition is described by

$$\mathcal{L}_{\text{eff}} = -\frac{\lambda_L^{32} \lambda_L^{*22}}{2m_\Delta^2} \bar{s} \gamma^\mu P_R b \bar{\mu} \gamma_\mu P_L \mu + \text{H.c}$$

The $b \to c\tau\nu$ transition is described by

$$\mathcal{L}_{\text{eff}} = (V_{CKM} \lambda_R)^{23} \lambda_L^{*33} \left[ \bar{c} P_R b \bar{\tau} P_R \nu + \frac{1}{4} \bar{c} \sigma_{\mu\nu} P_R b \bar{\tau} \sigma^{\mu\nu} P_R \nu \right]$$

Considering the couplings to the first generation to be zero

$$\lambda_{L,R} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \lambda_{L,R}^{s\mu} & \lambda_{L,R}^{s\tau} \\ 0 & \lambda_{L,R}^{b\mu} & \lambda_{L,R}^{b\tau} \end{pmatrix}$$

The model can accommodate $R_K$, $R_{D(*)}$, and all flavour observables like $b \to s\nu\nu$, $D_s \to \ell\nu$, $B_s - \bar{B}_s$ mixing, etc.

Cons: Since NP contribution to $b \to s\mu\mu$ is mediated by RH currents, it predicts $R_K^* > 1$.

Also the RH neutrino is assumed to be light.
Two scalar Leptoquarks: 1703.09226

- In models with LQs generating LH vector operators the coupling structure of $b$ quark should be aligned to avoid $b \to s\nu\nu$ bounds.
- However for $R_{D(*)}$ anomaly the contribution $\propto V_{cb} \times 3rd \text{ gen coupl}$.
- These large couplings subject to stringent bounds from direct LHC search on $\tau\tau$ channel.
- Two scalar LQs one singlet ($\phi_1(3, 1, -2/3)$) and one triplet ($\phi_3(3, 3, -2/3)$) both with hypercharge $Y = -2/3$ which contribute to $R_{D(*)}$ and $b \to s\nu\nu$ in opposite direction.

\[
\begin{align*}
&\begin{array}{c}
\nu \\
b \\
\Phi_1 + \Phi_3 \\
c
\end{array} \\
&\begin{array}{c}
\tau \\
b
\Phi_1 - \Phi_3 \\
\nu
\end{array} \\
&\begin{array}{c}
\nu \\
\ell \\
\Phi_3 \\
s
\end{array}
\end{align*}
\]
The coupling of $\Phi_1$ and $\Phi_3$ to the fermions are as

$$\mathcal{L} = \lambda_{fi}^{1L} \bar{Q}_i^c i \tau_2 L_i \Phi_1^\dagger + \lambda_{fi}^{3L} \bar{Q}_i^c i \tau_2 (\tau \cdot \Phi_3)^\dagger L_i + \text{H.c}$$

Both the LQs are assumed to have the same mass. To cancel their contribution to $b \to s \nu \nu$ impose the discrete symmetry

$$\lambda_{jk}^{1L} = \lambda_{jk}^L, \quad \lambda_{jk}^{3L} = e^{i\pi j} \lambda_{jk}^L$$

The model can naturally explain $b \to s \mu \mu$ (including $R(K^*)$) via $C_9 = -C_{10}$ contribution and predicts $R_{K^*} < R_{K^*}^{\text{SM}}$. 

![Graphs showing $\lambda_{23}$ and $\text{Br}(B_s \to \tau \tau)$](image)
Vector LQ $U_1^{\mu}(3, 1, 2/3)$: 1609.04367, 2004.09464, 1511.06024, …

- Vector LQ $U_1^{\mu}(3, 1, 2/3)$ with $Y = 2/3$ and $F = 0$ can mediate $b \rightarrow s\ell\ell$ and $b \rightarrow c\ell\nu$

- The int. Lagrangian of $U_1^{\mu}$ LQs with the SM fermion bilinear in int basis

$$\mathcal{L} = \left( h^{ij}_{1L} \bar{Q}_i \gamma^\mu L_j + h^{ij}_{1R} \bar{d}_i \gamma^\mu l_j \right) U_1^{\mu},$$

- Down type quark fields are rotated into the mass basis by the $V_{CKM}$

- Fierz transformation gives new WC to the $b \rightarrow c\tau\bar{\nu}$,

$$C_{V_1} = \frac{1}{2\sqrt{2} G_F V_{cb}} \sum_{k=1}^{3} V_{k3} \left[ \frac{h^{2L}_{1L} h^{k3*}_{1L}}{M^2 U_1^{2/3}} \right],$$

- The new WC for $b \rightarrow s\ell\ell$

$$C_{9}^{NP} = -C_{10}^{NP} = \frac{\pi}{\sqrt{2} G_F V_{tb} V_{ts}^* \alpha} \left[ \frac{h^{2L}_{1L} h^{k3*}_{1L}}{M^2 U_1^{2/3}} \right]$$
Summary

- Building a viable model which accommodates the observed B anomalies and consistent with all other measured flavor observables is difficult.
- Models with leptoquarks seem to address the anomalies along with some additional assumptions
- But they do not provide a clear picture of an UV complete model.

Thank you for your attention.