B-physics Anomalies: from Data to New Physics Models

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New Physics and Flavor

With a few exceptions, flavor-changing observables agree with the SM.

- If NP has a generic flavor structure, flavor bounds force it to be very heavy: \( \bar{K}K, \mu \to e\gamma \ldots \Rightarrow \Lambda > 10^{4-5} \text{ TeV} \)
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  e.g. Minimal Flavor Violation:
  $Y_{SM}$ only source of flavor violation (up to $\Lambda \gg 1$ TeV)
  → TeV-scale NP is flavor blind
  → by construction little to no effects in flavor obs.
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  \( \rightarrow \) TeV-scale NP is flavor blind
  
  \( \rightarrow \) by construction little to no effects in flavor obs.

- Now we have hints from flavor, the B anomalies.
  
  Taking them as genuine BSM signals, what do learn about the scale and flavor structure of New Physics?
Data
The $B$-physics anomalies

In the SM:

Gauge interactions are lepton-flavor universal. Lepton masses are the only source of non universality.

\[ \Gamma_e = \Gamma_\mu = \Gamma_\tau \]
(up to kinematical effects)
The $B$-physics anomalies

In the SM:

Gauge interactions are lepton-flavor universal.
Lepton masses are the only source of non universality.

Hints of LFU violation in semi-leptonic B decays:

- $\mu$ vs $e$ universality in $b \to sll$

  $$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)} < R_{K^{(*)}}^{SM}$$

  + angular obs. and rates in $b \to s\mu\mu$

  $\sim 4\sigma$

- $\tau$ vs $\mu, e$ universality in $b \to c\nu$

  $$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}e\bar{\nu})} > R_{D^{(*)}}^{SM}$$

  $\sim 3\sigma$

$$\Gamma_e = \Gamma_\mu = \Gamma_\tau$$
(up to kinematical effects)
The $b \rightarrow sll$ anomalies

- discrepancy in $B \rightarrow K^* \mu \mu$ angular distribution
- deficit in $\mathcal{B}(B \rightarrow X_s \mu \mu)$ $X_s = K, K^*, \phi$

- $\mu/e$ LFUV in $B \rightarrow K^{(*)} ll$
- deficit in $\mathcal{B}(B_s \rightarrow \mu \mu)$

LHCb results on LFU ratios this year:

- $R_{K^{(*)}}^{[1.1,6]} \text{ GeV}^2 = 1.00 \pm 0.01$ [Bordone et al, 1605.07633]
- $\mathcal{B}(B_s \rightarrow \mu \mu)_{\text{SM}} = (3.66 \pm 0.14) \times 10^{-9}$ [Beneke et al., 1908.07011]

Global significance for New Physics in $b \rightarrow sll \sim 4 \sigma$ [Isidori, Lancierini, Owen, Serra, 2104.05631]
The $b \rightarrow cl\nu$ anomalies

- $\sim 15\%$ enhancement due to excess in tau mode
- theoretically clean
- measurements by Babar, Belle, LHCb (so far $R_{D^{(*)}}$ only) in good agreement
- $3.1\sigma$ tension (combined)

Lower significance, need experimental clarification.
NP interpretation (I): Effective Theory
EFT for $b \rightarrow s\ell\ell$

$$\mathcal{L}_{\text{eff}} = - \frac{4G_F}{\sqrt{2}} V^*_{ts} V_{tb} \frac{\alpha}{4\pi} \sum_i C_i O_i$$

- $O^\mu_9 = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu} \gamma^\mu \mu)$
- $O^\mu_{10} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu} \gamma^\mu \gamma_5 \mu)$

$\Delta C^\mu_9 = - \Delta C^\mu_{10}$

- NP in $C^\mu_9$ only
- left-handed LFUV NP + subleading LFU shift

\[ \Delta C^\mu_9 \gtrsim 5 \sigma \]

- clean obs. only $4.6 \sigma$
- all obs., marginalizing in $\Delta C^U_9$ $4.8 \sigma$
- all obs. + estimate of $c\bar{c}$ loop $\gg 5 \sigma$

$[2103.13370, 2104.0892. 2104.10058...]$
EFT for $b \rightarrow c\tau\nu$

$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{cb} \sum_i C_i O_i$

$O_{LL}^i = (\bar{u}_L^i \gamma_\mu \nu_L)(\bar{\tau}_L \gamma^\mu b_L)$  \hspace{1cm} $C_{SM}^{LL} = 1$

$O_{LR}^i = (\bar{u}_L^i \gamma_\mu \nu_L)(\bar{\tau}_R \gamma^\mu b_R)$  \hspace{1cm} $C_{SM}^{LR} = 0$

- left-handed NP (=Fermi interaction!)
- other structures also possible

$\sim 40 \text{ TeV}$

$\sim 10^{-2} \, G_F$

Few TeV

$\mathcal{M}_{W, t, H}$
Why both?

No obvious connection. Why combine both anomalies in a single NP framework?

\[ b \to sll \quad \text{(} \bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L) \quad \text{SU}(2)_L \quad \text{b} \to c\ell\nu \quad \text{(} \bar{c}_L \gamma^\mu b_L)(\bar{\ell}_L \gamma_\mu \ell_L) \]

⇒ Minimal sol: left-handed NP in semi-leptonic operators (RH currents also possible)

\[ \mathcal{L}_{\text{EFT}}^{\text{NP}} = -\frac{1}{v^2} \left( C_{lq}^{(3)}(\bar{I}_L \gamma^\mu I_L)(\bar{q}_L \gamma^\mu q_L) + C_{lq}^{(1)}(\bar{I}_L \gamma^\mu I_L)(\bar{q}_L \gamma^\mu q_L) \right) \approx -\frac{2}{v^2} C_{LL}(\bar{q}_L \gamma^\mu q_L)(\bar{I}_L \gamma_\mu I_L) \]

Connection between anomalies:

\[ R_D^{(*)} \Rightarrow b_L \to c_L \tau_L \nu_L \sim b_L \to s_L \tau_L \tau_L \Rightarrow \]

\[ \mathcal{V}_{X} \vDash e, \mu, \tau \]

\[ \Delta C_U^9 \]
Why both?

**FLAVOR HIERARCHIES**

standard LFUV

\[ y_3 \gg y_2 \gg y_1 \]

**FLAVOR ANOMALIES**

non-standard LFUV

NP couples mostly to 3rd family, smaller couplings to 2nd and 1st.
Why both?

**FLAVOR HIERARCHIES**

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**FLAVOR ANOMALIES**

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NP couples mostly to 3rd family, smaller couplings to 2nd and 1st.

\[ U(2)^5 = U(2)_q \times U(2)_l \times U(2)_u \times U(2)_d \times U(2)_e \]

\[ \psi = (\psi_1 \psi_2 \psi_3) \]
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SM masses & mixings, “flavored”
alternative to MFV  \[ \text{[Barbieri et al.,1105.3396]} \]

\[ Y = y_3 \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \]

\[ y_3 \gg y_2 \gg y_1 \]

\[ |V_q| = \epsilon_q = \mathcal{O}(y_t |V_{ts}|) \quad |\Delta_{u,d,e}| \sim y_{c,s,\mu} \]
Why both?

\[ U(2)^5 = U(2)_q \times U(2)_l \times U(2)_u \times U(2)_d \times U(2)_e \]

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alternative to MFV \[ [\text{Barbieri et al., 1105.3396}] \]

\[ Y = y_3 \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \]

exact \( U(2)^5 \)

\[ |V_q| = \epsilon_q = \mathcal{O}(y_t V_{ts}) \quad |\Delta_{u,d,e}| \sim y_{c,s,\mu} \]

NP coupled only to 3rd family

NP max for 3rd family, suppressed by \( \epsilon_q (\epsilon_l) \)
for each 2nd family quark (lepton)

SM masses & mixings, "flavored"
alternative to MFV \[ [\text{Barbieri et al., 1512.01560}] \]

\[ Y = y_3 \begin{bmatrix} \Delta & V \\ 0 & 1 \end{bmatrix} \]

minimally broken \( U(2)^5 \)
EFT for combined explanations (LL)

\[ \mathcal{L}_{NP}^{EFT} = - \frac{2}{v^2} C_{LL}^{ij\alpha\beta} (\bar{q}_L^i \gamma_{\mu} l_L^j) (\bar{l}_L^\beta \gamma_{\mu} q_L^i) \]

- Data support U(2) scaling,
  \[ C_{LL}^{33\tau\tau} \sim 0.1 \]
  \[ C_{LL}^{23\tau\tau} \sim \epsilon_q C_{LL}^{33\tau\tau} \quad \epsilon_q, \epsilon_l \sim 0.1 \]
  \[ b \rightarrow s \mu^+ \mu^- \text{ observables} \]

- good consistency between the anomalies

\[ \frac{R_{D}^{(s)}}{R_{D}^{SM}} - 1 = 2 \text{Re} \left( C_{LL}^{33\tau\tau} + \frac{V_{cs}}{V_{cb}} C_{LL}^{23\tau\tau} \right) \]
EFT for combined explanations (LL)

\[ \mathcal{L}_{\text{EFT}}^{\text{NP}} = -\frac{2}{\nu^2} C_{LL}^{i\alpha\beta} (\bar{q}_i \gamma^\mu l_\alpha)(\bar{l}_\beta \gamma^\nu q_i) \]

- Data support U(2) scaling,
  \[ C_{LL}^{33\tau\tau} \sim 0.1 \]
  \[ C_{LL}^{23\tau\tau} \sim \epsilon_q C_{LL}^{33\tau\tau} \quad \epsilon_q, \epsilon_l \sim 0.1 \]
  \[ C_{LL}^{23\mu\mu} \sim \epsilon_q \epsilon_l C_{LL}^{33\tau\tau} \]

- good consistency between the anomalies

- several constraints (driven by \( R_D^{(\tau)} \))

\[ \frac{R_D^{(\tau)}}{R_D^{(\tau)}_{\text{SM}}} - 1 = 2\text{Re} \left( C_{LL}^{33\tau\tau} + \frac{V_{cs}}{V_{cb}} C_{LL}^{23\tau\tau} \right) \]
EFT for combined explanations (LL + LR)

\[ \mathcal{L}_{\text{EFT}}^{NP} = -\frac{2}{\nu^2} \left[ C_{i\ell}^{j\alpha} \left( \bar{q}^i_L \gamma^\mu l^\alpha_L \right) \left( \bar{l}^\beta_R \gamma^\mu q^i_L \right) + \left( C_{iR}^{j\alpha} \left( \bar{q}^i_L \gamma^\mu L^\alpha_L \right) \left( \bar{e}^\beta_R \gamma^\mu d^i_R \right) \right) + C_{iR}^{j\alpha} \left( \bar{d}^i_R \gamma^\mu e^\alpha_R \right) \left( \bar{e}^\beta_R \gamma^\mu d^i_R \right) \right] + \ldots \]

- LR helps saturating \( R_{D(*)} \)
  \( \rightarrow \) \( \tau \) LFU and \( B_s - \bar{B}_s \) less stringent.
- Both chiralities enter \( pp \rightarrow \tau\tau \)
  \( \rightarrow \) stronger high-\( p_T \) bounds.

![Graph showing the relationship between \( C^{33\tau\tau}_{LL} \) and \( C^{33\tau\tau}_{LL} \) with various observables and bounds indicated.]

[CC, Fuentes et al., 2103.16558]
NP interpretation (II): the $U_1$ simplified model
Which mediator?

- Only leptoquarks (scalars & vectors) are viable tree-level mediators
  - ✓ no 4-lepton and 4-quark processes at tree level
  - ✓ no resonant production in quark-quark initiated processes

- Three possibilities for a combined explanation:
  - $S_1 + S_3$ [Crivellin et al 1703.09226; Buttazzo et al. 1706.07808; Marzocca 1803.10972...]
  - $R_2 + S_3$ [Bećirević et al., 1806.05689]
  - $U_1 \sim (3, 1, 2/3)$ [di Luzio et al., 1708.08450; Calibbi et al., 1709.00692; Bordone, CC, et al. 1712.01368; Barbieri, Tesi 1712.06844; Heck,Teresi 1808.07492...]

  ✓ no $b \rightarrow s\nu\bar{\nu}$ at tree level

<table>
<thead>
<tr>
<th>Model</th>
<th>$R_K(\ast)$</th>
<th>$R_D(\ast)$</th>
<th>$R_K(\ast)$ &amp; $R_D(\ast)$</th>
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</tr>
<tr>
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<td>x</td>
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<tr>
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<td>$U_1$</td>
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[Sumensari et al., 2103.12504]
The $U_1$ simplified model

$$
\mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[ \beta_L^{i\alpha} (\bar{q}_L^i \gamma_{\mu} \ell_L^\alpha) + \beta_R^{i\alpha} (\bar{d}_R^i \gamma_{\mu} e_R^\alpha) \right] + \text{h.c.} \quad U_1 \sim (3, 1, 2/3)
$$

$$
\beta^L = \begin{pmatrix}
0 & 0 & \beta_{d\tau}^L \\
0 & \beta_{s\mu}^L & \beta_{s\tau}^L \\
0 & \beta_{b\mu}^L & \beta_{b\tau}^L
\end{pmatrix} \quad \beta^R = \begin{pmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & \beta_{b\tau}^R
\end{pmatrix}
$$

$\beta_{b\tau} = 1$

$\beta_{b\tau}^R \sim O(1)$

$\beta_{s\tau}, \beta_{b\mu}^L \sim O(0.1)$

$\beta_{s\mu}, \beta_{d\tau}^L \sim O(0.01)$

**Benchmarks:**

1. $\beta_{b\tau}^R = 0$

2. $|\beta_{b\tau}^R| = |\beta_{b\mu}^L| = 1$ [models with 3rd family quark-lepton unification]

✓ Good description of all low-energy data with U(2)-like flavor structure.
The $U_1$ simplified model

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[ \beta_L^{i\alpha} (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) + \beta_R^{i\alpha} (\bar{d}_R^i \gamma_\mu \ell_R^\alpha) \right] + \text{h.c.} \quad U_1 \sim (3,1,2/3)$$

$$\beta^L = \begin{pmatrix} R_{K(*)} & \tau \rightarrow \mu \gamma \text{ [loop]} \\ R_{D(*)} & b \rightarrow s \tau \mu \text{ [tree]} \\ \end{pmatrix} \quad \beta^R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta_{b\tau}^R \end{pmatrix} \quad\beta_{b\tau}^L = 1 \quad \beta_{b\tau}^R \sim \mathcal{O}(1) \quad \beta_{s\tau}^L, \beta_{b\mu}^L \sim \mathcal{O}(0.1) \quad \beta_{s\mu}^L, \beta_{d\tau}^L \sim \mathcal{O}(0.01)$$

**Benchmarks:**
1. $\beta_{b\tau}^R = 0$
2. $|\beta_{b\tau}^R| = |\beta_{b\tau}^L| = 1$ [models with 3rd family quark-lepton unification]

✓ Good description of all low-energy data with U(2)-like flavor structure.
Low-energy predictions for the $U_1$

- **large $b \to s\tau\tau$**

  - with RH currents
    - $\beta_{R}^{b\tau} = -1$

  - no RH currents
    - $\beta_{R} = 0$

  Excluded at 95% CL

  LHCb (300 fb$^{-1}$)

- **large $\tau/\mu$ LFV in $b \to s\tau\mu$ and $\tau$ decays**

  - with RH currents
    - $\beta_{R}^{b\tau} = -1$

  - no RH currents
    - $\beta_{R} = 0$

  Excluded at 95% CL

  [CC, Fuentes-Martin et al., 2103.16558]
High-pT bounds for the $U_1$

The same interaction can be probed in **di-tau tails**.

Expected excess in $pp \rightarrow \tau^+\tau^-$!  

[Faroughy et al, 1609.07138]

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**Graphical Content**

- **No RH currents** $[\beta_R = 0]$
- **With RH currents** $[\beta_R^{br} = -1]$

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**Legend**

- $pp \rightarrow \tau\tau$ (13 TeV $137 \text{ fb}^{-1}$)
- $pp \rightarrow \tau\tau$ (13 TeV $13 \text{ ab}^{-1}$)
- $pp \rightarrow \tau\tau$ (13 TeV $3 \text{ ab}^{-1}$)

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**Axes**

- $g_U$ on y-axis
- $M_U$ [TeV] on x-axis

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**Additional Details**

- Graphs show bounds for different interaction scenarios.
- The transition from no RH currents to with RH currents demonstrates the impact on the observed bounds.

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**Referenced Works**

- [Faroughy et al, 1609.07138]
- [CC, Fuentes-Martin et al., 2103.16558]
NP interpretation (III): UV completing the $U_1$
UV-completing the $U_1$: the gauge path

$U_1 \sim (3,1,2/3) \longrightarrow SU(4) \longrightarrow \text{PS} = SU(4) \times SU(2)_L \times SU(2)_R$

\[
SU(4) \sim \begin{pmatrix} G^a & U^a \\ (U^a)^* & Z' \end{pmatrix}
\]

$\psi_{L,R} = \begin{bmatrix} q^a_{L,R} \\
q^\beta_{L,R} \\
q^\gamma_{L,R} \\
l^\delta_{L,R} \end{bmatrix}$

\[\text{PS/SM} \ni U_1, Z' \]

- flavor-blind $U_1$ mediates $K_L \rightarrow \mu e \Rightarrow m_{U_1} \gtrsim 100 \text{ TeV}$
- *extra fermions can make the $U_1$ non-universal, not the $Z'$
- strongly coupled, universal $Z'$ would be excessively produced at the LHC

UV-completing the $U_1$: the gauge path

$U_1 \sim (3,1,2/3) \rightarrow SU(4) \rightarrow PS = SU(4) \times SU(2)_L \times SU(2)_R$

$SU(4) \sim \left(\begin{array}{c}
G^a \\
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Z'
\end{array}\right)$

$\psi_{L,R} = \left[\begin{array}{c}
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PS/SM $\ni U_1, Z'$(strongly coupled & flavor universal*)

$\times$ flavor-blind $U_1$ mediates $K_L \rightarrow \mu e \Rightarrow m_{U_1} \gtrsim 100$ TeV

$\times$ *extra fermions can make the $U_1$ non-universal, not the $Z'$

$\times$ strongly coupled, universal $Z'$ would be excessively produced at the LHC

$G_{4321} = SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$

$4321/SM \ni U_1, Z', G' \sim (8,1,0)$

$\checkmark$ $SU(4)$ decorrelated from $SU(3)_c$. High-pT problem solved for $g_4 \gg g_1, g_3$

$\checkmark$ both $Z'$ and $U_1$ can be flavor non-universal

[Georgi and Y. Nakai, 1606.05865; Diaz, Schmaltz, Zhong, 1706.05033; Di Luzio, Greljo, Nardecchia, 1708.08450]
Non-universality via mixing

\[ \mathcal{G}_{4321} = SU(4) \times SU(3)' \times SU(2)_L \times U(1)' \]

- flavor-universal gauge interactions
  - all SM families have SM-like charges under 321
  - only vector-like fermions are charged under 4

- no direct NP couplings to SM fields.

\[ \Psi = \begin{pmatrix} Q \\ L \end{pmatrix} \]

- flavor structure of \( U_1 \) interactions for B anomalies generated via hierarchical choice of mixing angles
  \[ \rightarrow \text{3rd family has to be the } \text{“most composite”} \]

- can have \( U_1 \) coupled only to left-handed SM fields

- Yukawa couplings as in the SM. No connection flavor anomalies & hierarchies.

[di Luzio, Greljo, Nardecchia, 1708.08450; di Luzio, Fuentes-Martin, Greljo, Nardecchia, Renner 1808.00942]
Non-universal gauge interactions

\[ G_{4321} = SU(4)_3 \times SU(3)_{1+2} \times SU(2)_L \times U(1) \]

- **flavor non-universal gauge interactions**
  - light SM families: SM-like charges under 321
  - vectorlike fermions and 3rd SM family charged under 4
    - accidental \( U(2)^5 \)
    - direct NP coupling to 3rd SM family (L+R)
    - TeV scale 3rd family quark-lepton unification
Non-universal gauge interactions

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- flavor non-universal gauge interactions
  - light SM families: SM-like charges under 321
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    - accidental \( U(2)^5 \)
    - direct NP coupling to 3rd SM family (L+R)
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- \( U(2)^5 \) broken by SM-vectorlike mixing

<table>
<thead>
<tr>
<th>Field</th>
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Leading breaking:
- \( U_1 \) couplings to light families for B anomalies
- 2-3 CKM mixing
  - connection flavor anomalies & hierarchies!

Subleading breaking:
- constrained by \( K_L \rightarrow \mu e \), \( K-\bar{K} \) and \( D-\bar{D} \)

\[ \text{Mild 2-3 down alignment required to suppress } G' \text{ and } Z' \text{ contribution to } B_s - \bar{B}_s \]
UV-sensitive low-energy observables

- $B_s - \bar{B}_s$ mixing

$$\frac{C_{bs}^{\text{NP-tree}}}{C_{bs}^{\text{SM}}} \propto \left( \beta_L^{b\tau*} \right)^2 M_L^2$$

$U(2)_q$ breaking (for $R_{D^{(*)}}$)

→ vector-like leptons must be light, in the reach of the LHC

- $B \rightarrow K\nu\bar{\nu}$

→ 20-50% enhancement over the SM (also driven by $R_{D^{(*)}}$), in the reach of Belle II

[Selimovic et al., 2009.11296]
[CC, Fuentes et al., 2103.16558]
Coloron direct searches at the LHC

Relevant collider signatures for $G'$
(“coloron” = heavy color-octet vector)

$G'$-mediated $pp \rightarrow tt$ gives the strongest constraint on the overall scale of the model!

$$M_{G'} \sim \sqrt{2} M_{LQ}$$
B anomalies might hint at a three-scale picture:

New, non-universal interactions (for us: gauge) acting on the i-th SM family switch on at $\Lambda_1 \gg \Lambda_2 \gg \Lambda_3 \gg m_W$.

Yukawa couplings are different because they originate at these different scales.

New Physics is flavor non-universal; universality is a low-energy accident.

$\Lambda_3$ can be as low as few TeV.
Non-universal Pati-Salam unification

**PS³: 4D three-site model**

1. **1st Family**
   - \( \Sigma_1 \)
   - \( \Phi^R_{12} \)
   - \( \Phi^L_{12} \)
   - \( \Omega_{12} \)
   - \( \Sigma_1 \)

2. **2nd Family**
   - \( \Phi^R_{23} \)
   - \( \Phi^L_{23} \)
   - \( \Omega_{23} \)
   - \( \Sigma_1 \)

3. **3rd Family**
   - \( \Phi^L_{31} \)
   - \( \Omega_{31} \)
   - \( \Sigma_1 \)

\( \Lambda_1 > E > \Lambda_{12} \)
\( \Lambda_{12} > E > \Lambda_{23} \)
\( \Lambda_{23} > E > \Lambda_3 \)

- \( \langle \Phi^R_{12} \rangle \)
- \( \langle \Phi^L_{12} \rangle \)
- \( \langle \Phi^L_{23} \rangle \)

- \( \langle \Omega_{12} \rangle \)
- \( \langle \Omega_{23} \rangle \)
- \( \langle \Omega_{31} \rangle \)

\[ \text{SU}(4)_3 \times \text{SU}(3)_{1+2} \times \text{SU}(2)_L \times U(1)' \]

- **5D construction**
  - warped compact extra dimension with multiple 4-dimensional branes

- **1st Family**
  - \( S_L^{(1)} \)
  - \( \psi_L^{(1)} \)
  - \( \Phi_L \)

- **2nd Family**
  - \( S_L^{(2)} \)
  - \( \psi_L^{(2)} \)

- **3rd Family**
  - \( S_L^{(3)} \)
  - \( \psi_L^{(3)} \)

- **1st Family**
  - \( f_{12}^{-1} \)

- **2nd Family**
  - \( f_{23} \)

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[Bordone, CC, Fuentes, Isidori 1712.01368]
[Fuentes-Martin, Isidori, Pagès, Stefanek, 2012.10492]
[Fuentes-Martin, Isidori, Lizana, Stefanek, Selimovic, in progress]
NP interpretation (IV): g-2 in 4321 models

[inspired by Ben Stefanek’s Virtual Seminar @ Peking and Beijing Flavor Anomaly Seminar Series on June 17, 2021]
\((g - 2)_\mu\) as New Physics

The discrepancy is roughly the same size as the SM electroweak contribution:

\[
\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} \approx (a_\mu^{\text{SM}})_{\text{EW}} \approx \frac{m_\mu^2}{16\pi^2} \times \frac{4G_F}{\sqrt{2}} \approx 3 \times 10^{-9}
\]

\[\Rightarrow \text{New physics scale?}\]

\[
\langle H \rangle \gamma \langle H \rangle
\]

\[
\ell^i_L \ell^j_R
\]

\[
\Delta a_\mu^{\text{NP}} \approx \frac{g_{\text{NP}}^2}{16\pi^2} \frac{m_\mu^2}{M_{\text{NP}}^2}
\]

\[
\Rightarrow M_{\text{NP}} \sim \nu_{\text{EW}}
\]

\[
\Delta a_\mu^{\text{NP}} \approx \frac{g_{\text{NP}}^2}{16\pi^2} \frac{m_\mu m_f}{M_{\text{NP}}^2}
\]

\[\Rightarrow M_{\text{NP}} \sim \sqrt{N_c} \left\{ \begin{array}{ll}
1 \text{ TeV} & m_f = m_b \\
6 \text{ TeV} & m_f = m_t
\end{array} \right. \quad (\text{Max } \sim 10 \text{ TeV})
\]

*Another option is light NP \(M_{\text{NP}} < \nu_{\text{EW}}\) with small couplings.
$(g - 2)_\mu$ as New Physics

\[ \mathcal{L}_{\text{EFT}} \supset \frac{e}{16\pi^2} \frac{v}{\sqrt{2}} C_{\ell\ell'} (\bar{\ell}_L \sigma_{\mu\nu} \ell'_R F^{\mu\nu}) \]

\[ \ell = \ell': \text{Magnetic & electric moments} \]
\[ (g - 2)_\mu \rightarrow \text{Re}(C_{\mu\mu}) \approx (4 - 7) \times 10^{-3} \text{ TeV}^{-2} \]
\[ \text{eEDM} \rightarrow \text{Im}(C_{ee}) \lesssim 10^{-10} \text{ TeV}^{-2} \]

\[ \ell \neq \ell': \text{cLFV, in particular } \ell \rightarrow \ell' \gamma \]
\[ \mu \rightarrow e\gamma \quad \rightarrow \quad |C_{\mu e}| \lesssim 10^{-7} \text{ TeV}^{-2} \]
\[ \tau \rightarrow \mu\gamma \quad \rightarrow \quad |C_{\tau\mu}| \lesssim 2 \times 10^{-3} \text{ TeV}^{-2} \]

[Calibbi, Lopez-Ibanez, Melis, Vives, 2104.03296]

\[ \Rightarrow \text{cLFV bounds require strong alignment} \quad C_{\mu e}/C_{\mu\mu} \lesssim 10^{-5}, \quad C_{\tau\mu}/C_{\mu\mu} \lesssim 0.5 \]

much stronger than what naively expected from Yukawa-like flavor structure:

\[ C_{\mu e}/C_{\mu\mu} \sim \sqrt{m_e/m_\mu} \approx 0.07, \quad C_{\tau\mu}/C_{\mu\mu} \sim \sqrt{m_\tau/m_\mu} \approx 4 \]

\[ \Rightarrow \text{Not easy to reconcile } (g - 2)_\mu \text{ with both } B \text{ anomalies.} \]
U$_1$ for both anomalies and g-2?

We already know the U$_1$ leptoquark works for B-anomalies. What about for (g-2)?

Need large U$_1$ coupling to $\mu_R, b_R$:

\begin{align*}
\Delta a_\mu &\sim \frac{N_c}{4\pi^2} \frac{m_\mu m_b}{M_{LQ}^2} \frac{g_4^2}{2} s_{\mu_L}s_{\mu_R} \\
&\sim 10^{-9} \left(\frac{3 \text{ TeV}}{m_{LQ}}\right)^2 \left(\frac{s_{\mu_L}}{0.2}\right) \left(\frac{s_{\mu_R}}{0.2}\right)
\end{align*}

But RH currents generate the scalar operator

$$\mathcal{O}_s \sim \frac{m_b}{m_\mu} V_{ts} \left(\bar{s}_L b_R\right) \left(\bar{\mu}_R \mu_L\right)$$

….would give too large a contribution to $B_s \rightarrow \mu^+\mu^-$!
U₁ for both anomalies and g-2?

Try with vector-like fermions in the loop:

\[ \chi_{L,R} \sim (4,1,2,0), \quad \xi \supset (Q_L), \quad \xi \supset (D_E) \]
\[ \xi_{L,R} \sim (4,1,1, -1/2) \]

VL mass contribution from Higgs:

\[ \mathcal{L} \supset -\bar{\chi}_L y_H H \xi_R - \bar{\chi}_R \tilde{y}_H H \xi_L \]

\[ \Delta a_\mu \sim \frac{N_c}{4\pi^2} \frac{m_\mu m_t}{M_{LQ}^2} \frac{g_4^2}{2} y_H s_{\mu_L} s_{\mu_R} \]
\[ \sim 3 \times 10^{-9} \left( \frac{4 \text{ TeV}}{m_{LQ}} \right)^2 \left( \frac{s_{\mu_L}}{0.2} \right) \left( \frac{s_{\mu_R}}{0.05} \right) \left( \frac{y_H}{1} \right) \]

✓ for \( y_H, \tilde{y}_H \sim 1 \), get full chiral enhancement!
U\textsubscript{1} for both anomalies and g-2?

Try with vector-like fermions in the loop:

\[ \chi_{L,R} \sim (4,1,2,0), \quad \chi \supset \left( \begin{array}{c} Q \\ L \end{array} \right), \quad \xi \supset \left( \begin{array}{c} D \\ E \end{array} \right) \]

\[ \xi_{L,R} \sim (4,1,1,-1/2) \]

VL mass contribution from Higgs:

\[ \mathcal{L} \supset -\bar{\chi}_{L} y_{H} H \xi_{R} - \bar{\chi}_{R} \tilde{y}_{H} H \xi_{L} \]

\[ \Delta a_{\mu} \sim \frac{N_{c} m_{\mu} m_{t}}{4 \pi^{2} M_{LQ}^{2}} \frac{g_{4}^{2}}{2} y_{H} s_{\mu_{L}} s_{\mu_{R}} \sim 3 \times 10^{-9} \left( \frac{4 \text{ TeV}}{m_{LQ}} \right)^{2} \left( \frac{s_{\mu_{L}}}{0.2} \right) \left( \frac{s_{\mu_{R}}}{0.05} \right) \left( \frac{y_{H}}{1} \right) \]

\[ \checkmark \text{ for } y_{H}, \tilde{y}_{H} \sim 1, \text{ get full chiral enhancement!} \]

\[ \times \text{ SM chiral - VL mixing gives large tree-level correction to down-type Yukawas} \]

\[ y_{\mu} = y_{\mu}^{H} + \delta y_{\mu}^{\text{mix}} + \delta y_{\mu}^{\text{loop}} \sim 6 \times 10^{-4} \]

\[ \delta y_{\mu}^{\text{mix}} \sim y_{H} s_{\mu_{L}} s_{\mu_{R}} \sim 10^{-2} \]

\[ \times \text{ no control for cLFV. Main problem is the expectation for } \tau \rightarrow \mu \gamma: \]

\[ \frac{C_{\tau \mu}}{C_{\mu \mu}} \sim \frac{1}{s_{\mu_{L}}} \sim 5 \gg 0.5 \]

\[ \rightarrow \text{ U\textsubscript{1} vector LQ as a single mediator fails.} \]
A possible solution within universal 4321

Enlarge the scalar sector and add a softly broken $Z_2$ symmetry can work!

$$y_\mu = y_\mu^H + \delta y_\mu^{\text{mix}} + \delta y_\mu^{\text{loop}}$$

forbidden by $Z_2$

suppressed if $v_{1+/v_{1-}} \equiv \tan \beta_1 \gg 1$

$$\frac{v_1}{16\pi^2 M_\Omega} \approx 3 \times 10^{-9} \left( \frac{1 \text{ TeV}}{M_\Omega} \right)^2$$

large $\tan \beta_1$

$$\Delta a_\mu \approx \frac{m_\mu^2}{16\pi^2 M_\Omega^2} \approx \frac{m_\mu m_b}{16\pi^2 M_\Omega^2}$$

$[\text{Fuentes-Martin, Greljo, Stefanek, Thomsen, in progress}]$
Conclusions and outlook

$B$ anomalies could be the manifestation of a new interaction violating LFU. In the coming years, on-going experiments will have the final word about their nature!

- Taken together, they point to TeV-scale leptoquark(s) coupled dominantly to the 3rd family.
  - flavor non-universal gauge interactions?
  - multi-scale picture at the origin of flavor?

Explaining also the (g-2) is possible, but requires additional ingredients.

- Consistent picture, but present data in $b \rightarrow c\tau\nu$ require NP to be quite close: if $R_D^{(*)}$ stays, we NP effects must show up soon, at low and high energy.
  Need experimental corroboration to guide us.