Mostly Leptoquarks and some VL Fermions

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Anomalies in $b \rightarrow c$ semi-leptonics: $R_D$ and $R_{D^*}$

$R_{D^*} = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \rightarrow D^{(*)}\ell\bar{\nu})}$

$[\ell = e, \mu]$

2022 LHCb $\tau \rightarrow \mu$: first joint measurement of $R_D$ & $R_{D^*}$ at a hadron collider. Only Run 1 data. [LHCb, 2302.02886]

New! 2023 LHCb $\tau \rightarrow \text{had}$: $R_{D^*}$ with Run 1 + partial Run 2 data. Hadronic taus.

- Theoretically semi-clean. Measurements by Babar, Belle, LHCb in good agreement.
- Enhancement of $\sim 10\%$ over SM due to excess in tau mode: $B \rightarrow D^{(*)}\tau\bar{\nu}$.
- Combined, $3.2\sigma$ tension w.r.t SM. Measurement of $R_{\Lambda_c}/R_{\Lambda_c}^{SM} = 0.73 \pm 0.23$ reduces tension slightly. [LHCb, 2201.03497]
New physics in $b \rightarrow c\tau\nu$ decays

- We need ~10% of a tree-level SM process due to NP. Heavy NP should therefore also be tree-level to compete. Consider Fermi-like LH NP:

\[ \mathcal{A}_{NP} \approx \frac{1}{\Lambda_{NP}^2} \]

- The charged current $B$-anomalies are calling for a low NP scale!

\[
2 \frac{\mathcal{A}_{NP}}{\mathcal{A}_{SM}} = \frac{v^2}{V_{cb} \Lambda_{NP}^2} \approx \delta R_{D^*}^* \quad \Rightarrow \quad \Lambda_{NP} \approx \frac{v}{\sqrt{V_{cb} \delta R_{D^*}^*}} \approx 3.6 \text{ TeV} \left( \frac{0.12}{\delta R_{D^*}^*} \right)^{1/2}
\]
What kind of new particles could we have?

- LH NP $\implies b \rightarrow s\tau\tau(\nu\nu)$ couplings. LQ’s have two important advantages

1. $\Delta F = 2$ :

2. Direct searches: $t$-channel versus resonant $s$-channel production
Only leptoquarks are viable mediators!

LH NP $\rightarrow b \rightarrow s\tau\tau(\nu\nu)$ couplings. LQ’s have two important advantages

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2. Direct searches: t-channel versus resonant s-channel production
Shopping for Leptoquarks

- There are three viable options on the leptoquark market:

<table>
<thead>
<tr>
<th>Model</th>
<th>$R_K^(*)$</th>
<th>$R_D^(*)$</th>
<th>$R_K^(<em>) &amp; R_D^(</em>)$</th>
</tr>
</thead>
<tbody>
<tr>
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<td>$\times$</td>
<td>$\checkmark$</td>
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</tr>
</tbody>
</table>

Scalar Leptoquarks:
- $S_1 \sim (\bar{3}, 1, 1/3)$
  [Crivellin, Muller, Ota 1703.09226; Buttazzo et al. 1706.07808; Marzocca 1803.10972,…]
- $R_2 \sim (3, 2, 7/6)$
  [Bečirević et al., 1806.05689]

Vector Leptoquarks:
- $U_1 \sim (3, 1, 2/3)$ (Massive spin-1, requires UV completion)
  [di Luzio, Greljo, Nardecchia 1708.08450; Calibbi, Crivellin, Li 1709.00692; Bordone, Cornella, Fuentes-Martin, Isidori 1712.01368; Barbieri, Tesi, 1712.06844; Greljo, BAS, 1802.04274]
Which Leptoquark?

- There are three viable options on the leptoquark market:

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Which Leptoquark?

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  **Vector Leptoquarks:**
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  **Scalar Leptoquarks:**
  - $S_1 \sim (\bar{3},1,1/3)$ $R_2 \sim (3,2,7/6)$

- Only the $U_1$ vector LQ also gives a **flavor universal effect** in $b \to s\ell\ell$ via RGE:

  \[ b_L \tau_L \quad \xrightarrow{SU(2)_L} \quad b_L \tau_L \quad \xrightarrow{RGE} \ \Delta C_9^U = C_9^U - C_9^{SM} \]

  "Dirty" $b \to s\ell^+\ell^-$ anomalies prefer: $\Delta C_9^U \approx -0.75 \pm 0.25$
Simplified model for $U_1$ leptoquark

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[ (\bar{q}_L^3 \gamma_\mu \ell^3_L) + \beta_L^{s\tau} (\bar{q}_L^2 \gamma_\mu \ell^3_L) + \beta_{R}^{b\tau} (\bar{b}_R \gamma_\mu \tau_R) \right] + \text{h.c.} \quad U(2)_{q\text{-breaking}} \sim O(V_{cb})$$
Simplified model for $U_1$ leptoquark

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[ (\bar{q}^3_L \gamma_\mu \ell^3_L) + \beta^s_\tau (\bar{q}^2_L \gamma_\mu \ell^3_L) + \beta^b_\tau (\bar{b}_R \gamma_\mu \tau_R) \right] + \text{h.c.}$$

Integrate out the $U_1$ LQ:

$$\frac{1}{\Lambda_{NP}^2} = \frac{g_U^2}{2M_U^2}$$

**RUNNING to EW SCALE + MATCHING**

$$\mathcal{L}_{b \rightarrow c \tau \nu} = -\frac{2}{v^2} V_{cb} \left[ \left(1 + C_{LL}^c\right) (\bar{c}_L \gamma_\mu b_L) (\bar{\tau}_L \gamma_\mu \nu_L) - 2 C_{LR}^c (\bar{c}_L b_R) (\bar{\tau}_R \nu_L) \right]$$
Simplified model for $U_1$ leptoquark

$U_1 \sim (3, 1, 2/3)$

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[ (\bar{q}_L \gamma_\mu \ell_L^3) + \beta_L^{\ell_\tau} (\bar{q}_L \gamma_\mu \ell_L^3) + \beta_R^{b_\tau} (\bar{b}_R \gamma_\mu \tau_R) \right] + \text{h.c.}$$

Integrate out the $U_1$ LQ:

$$\frac{1}{\Lambda_{\text{NP}}^2} = \frac{g_U^2}{2 M_U^2}$$

RUNNING to EW SCALE + MATCHING

$$\mathcal{L}_{b \rightarrow c \tau \bar{\nu}} = -2 \frac{V_{cb}}{v^2} V_{cb} \left[ \left( 1 + C_{LL}^c \right) (\bar{c}_L \gamma_\mu b_L) (\bar{\tau}_L \gamma_\mu \nu_L) - 2 C_{LR}^c (\bar{c}_L b_R) (\bar{\tau}_R \nu_L) \right]$$

Contact interaction:

Low-energy WC’s ↔ Model parameters:

$$C_{LL}^c = \frac{g_U^2 v^2}{4 M_U^2} \left( 1 + \frac{V_{cs}}{V_{cb}} \beta_L^{\ell_\tau} \right), \quad C_{LR}^c = \beta_R^{b_\tau} C_{LL}^c$$
Low-energy fit for $U_1$ leptoquark model

$U_1 \sim (3, 1, 2/3)$

\[
\mathcal{L}_{b \rightarrow c\tau\bar{\nu}} = -\frac{2}{v^2} V_{cb} \left[ \left( 1 + C_{LL}^c \right) \left( \bar{c}_L \gamma_{\mu} b_L \right) \left( \bar{\tau}_L \gamma^\mu \nu_L \right) - 2 C_{LR}^c \left( \bar{c}_L b_R \right) \left( \bar{\tau}_R \nu_L \right) \right]
\]

$\delta R_D^{(*)} \approx 2C_{LL}^c - a_D^{(*)} C_{LR}^c \quad \{ a_D \approx 3.00 \quad a_D^* \approx 0.24 \}$

Low-energy WC’s ↔ Model parameters

$C_{LL}^c = \frac{g_{U}^2 v^2}{4M_U^2} \left( 1 + \frac{V_{cs}}{V_{cb}} \beta_{L}^{\tau} \right), \quad C_{LR}^c = \beta_{R}^{b\tau*} C_{LL}^c$

[Updated w/ HFLAV 2023]

Best-fit point
$C_{LL}^c = 0.048$
$C_{LR}^c = -0.016$

LH-only
$C_{LL}^c = 0.063$

$R_A_{[90\%]}$

$C_{LL}^c = 0.031$

$LH = -RH$

$C_{LL}^c = 0.031$

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Low-energy fit for $U_1$ leptoquark model

$$U_1 \sim (3, 1, 2/3)$$

$$\mathcal{L}_{b \to c \tau \bar{\nu}} = -\frac{2}{v^2} V_{cb} \left[ \left( 1 + C_{LL}^c \right) (\bar{c}_L \gamma_\mu b_L) (\bar{\tau}_L \gamma^\mu \nu_L) - 2 C_{LR}^c (\bar{c}_L b_R) (\bar{\tau}_R \nu_L) \right]$$

$$\delta R_D^{(*)} \approx 2C_{LL}^c - a_D^{(*)} C_{LR}^c$$

Low-energy WC's ↔ Model parameters

$$C_{LL}^c = \frac{g_U^2 v^2}{4M_U^2} \left( 1 + \frac{V_{cs}}{V_{cb}} \beta_s^{\tau} \right), \quad C_{LR}^c = \beta_R^{b\tau*} C_{LL}^c$$

Matching: NP scale and U(2)-breaking

$$\frac{1}{\Lambda_{NP}^2} = \frac{g_U^2}{2M_U^2}, \quad V_q = \beta_s^{\tau}$$

New physics scale preferred by low-energy fit:

$$\Lambda_{NP} \approx \{1.2, 1.5, 1.8\} \text{ TeV} , \quad (V_q = 0.1)$$

{LH-only, BFP, LH=-RH}

[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, 2210.13422]
High-energy searches: $U_1$ leptoquark

Caveat: BR=1 (CMS) vs BR=0.5 (ATLAS)

CMS-PAS-EXO-19-016

EXOT-2022-39

Large improvement in sensitivity when adding low b-jet $p_T$ category

Excludes CMS’ excess

[A. Juste, Moriond EW ’23]
UV Completion for the $U_1$ Leptoquark
UV Model: New flavor non-universal gauge interactions

Based on “4321” gauge symmetry:

\[ SU(4) \times SU(3)_c \times SU(2)_L \times U(1)_{l+R} \]

\[ \langle \Omega_{1,3,15} \rangle \sim \mathcal{O}(\text{TeV}) \]

\[ SU(3)_c \times SU(2)_L \times U(1)_Y \]

+ \[ U, G', Z' \]
UV Model: New flavor non-universal gauge interactions

Based on “4321” gauge symmetry:

\[ SU(4) \sim SU(3)_c \times SU(2)_L \times U(1)_Y + U_1, G', Z' \]

Third-family quark-lepton unification at the TeV scale: [Greljo, BAS, 1802.04274]

- 3rd family charged under \( SU(4)_h \) \( \implies \) Direct NP couplings (L+R)
- Light families under 321 (SM-like)
- Accidental approximate \( U(2)^5 \) flavor symmetry: \( \psi = (\underline{\psi_1 \, \psi_2 \, \psi_3}) \)
- Good starting point for CKM

Leptons as the fourth “color”


(only 7 years after the SM was proposed)

4321 models

[di Luzio, Greljo, Nardecchia 1708.08450
Bordone, Cornella, Fuentes-Martin, Isidori 1712.01368, 1805.09328;
Greljo, BAS, 1802.04274;
Cornella, Fuentes-Martin, Isidori 1903.11517]
UV Model: The origin of light-heavy CKM mixing

Third-family quark-lepton unification at the TeV scale: [Greljo, BAS, 1802.04274]

\[
\begin{align*}
\psi_L &\sim \begin{pmatrix} q^3_L \\ \ell^3_L \end{pmatrix} \\
\psi^+_R &\sim \begin{pmatrix} u^3_R \\ \nu^3_R \end{pmatrix} \\
\psi^-_R &\sim \begin{pmatrix} d^3_R \\ e^3_R \end{pmatrix} \\
\chi_{L,R} &\sim \begin{pmatrix} Q_{L,R} \\ L_{L,R} \end{pmatrix}
\end{align*}
\]
UV Model: The origin of light-heavy CKM mixing

Third-family quark-lepton unification at the TeV scale: [Greljo, BAS, 1802.04274]

\[ \psi_L \sim \begin{pmatrix} q^3_L \\ \ell^3_L \end{pmatrix} \quad \psi_R^+ \sim \begin{pmatrix} u^3_R \\ \nu^3_R \end{pmatrix} \quad \psi_R^- \sim \begin{pmatrix} d^3_R \\ e^3_R \end{pmatrix} \quad \chi_{L,R} \sim \begin{pmatrix} Q_{L,R} \\ L_{L,R} \end{pmatrix} \]

- CKM mixing via a vector-like quark. Generates $V_{cb}, V_{ub}$ as dimension-5 operators.

\[ \mathcal{L}_{\text{mix}} \supset -\lambda^i q^i \Omega_3 \chi_R - y_{\pm} \chi_R H \Psi_{R}^{\pm} \rightarrow \frac{y_{\pm} \lambda^i}{M_\chi} \bar{q}^i L \Omega_3 H \Psi_{R}^{\pm} \]

\[ \langle \Omega_3 \rangle \quad H \]

\[ \bar{q}^i_L \quad Q_R \quad \bar{Q}_L \quad M_Q \quad t_R/b_R \]
UV Model: Vector-like fermions

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\[
\begin{align*}
\psi_L & \sim \left( q_3^L \ell_3^L \right) \\
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\end{align*}
\]

Vector-like Lepton:

- Controls loop FCNC’s

\[
B \rightarrow K \nu \bar{\nu} \propto M_L
\]

\[
\Delta M_{B_s} \propto M_L^2
\]

[CMS-PAS-B2G-21-004]: \( M_L \gtrsim 500 \) GeV
UV Model: Vector-like fermions

Third-family quark-lepton unification at the TeV scale: [Greljo, BAS, 1802.04274]

\[ \psi_L \sim \left( \begin{array}{c} q_L^3 \\ \ell_L^3 \end{array} \right) \quad \psi_R^+ \sim \left( \begin{array}{c} u_R^3 \\ \nu_R^3 \end{array} \right) \quad \psi_R^- \sim \left( \begin{array}{c} d_R^3 \\ e_R^3 \end{array} \right) \quad \chi_{L,R} \sim \left( \begin{array}{c} Q_{L,R} \\ L_{L,R} \end{array} \right) \]

Vector-like Lepton:

- Controls loop FCNC’s

Vector-like Quark:

- CKM mixing and effects in EWPO via RGE

\[ \mathcal{L}_{\text{mix}} \supset -y_{\pm} \tilde{\chi}_L H \Psi^\pm_R \]

\[ B \rightarrow K\nu\bar{\nu} \propto M_L \]

\[ \Delta M_{B_s} \propto M_L^2 \]

[CMS-PAS-B2G-21-004]: \[ M_L \gtrsim 500 \text{ GeV} \]

[CMS-B2G-20-011]: \[ M_Q \gtrsim 1.5 \text{ TeV} \]
UV Model: New colored particles and EW observables

- In addition to the $U_1$ LQ, we also get neutral $G', Z'$ vectors.
- We also need a vector-like quark and lepton $Q, L$ for fermion mixing.
UV Model: New colored particles and EW observables

- In addition to the $U_1$ LQ, we also get neutral $G', Z'$ vectors.
- We also need a vector-like quark and lepton $Q, L$ for fermion mixing.
- New colored states $Q, G'$ give sizable shifts in the W-mass via RGE effects.

$$\frac{\Delta m_W}{m_W} \propto - \frac{v^2}{4} \frac{s_L^2}{s_L^2 - s_Y^2} C_{HD}$$

$$\mathcal{O}_{HD} = |H^+ D_\mu H|^2$$

$$\alpha T = - \frac{v^2}{2} C_{HD}$$

- Full EW fit in 4321 model: [Allwicher, Isidori, Lizana, Selimovic, BAS, 2302.11584]
Conclusions

- The tension in the LFU ratios $R_D^{(*)}$ remains an interesting hint of NP at the TeV scale. If we take it seriously, leptoquark models are the only viable mediators. **Important:** These models did not change much without $R_K^{(*)}$!

- Consistent picture, but present data in $b \to c\tau\nu$ require NP to be quite close: if the tension persists, NP effects must show up soon, at low and high energy.

- Of the mediators that can explain the charged-current B-anomalies, only the $U_1$ LQ connects $b \to c\tau\nu$ transitions to flavor universal effects in the $b \to s\ell\ell$ system.

- In UV complete models for the $U_1$ LQ (e.g. the 4321 model), CKM mixing requires the existence of light VL quarks and leptons that can be discovered at the LHC.

- The VLF’s give new loop-level pheno correlated with $R_D^{(*)}$, such as an $\sim50\%$ enhancement in $B \to K\nu\bar{\nu}$ and large positive shifts to the $W$-mass via RGE.

- From the phenomenological point of view, the implications of NP explanations of $R_D^{(*)}$ have been clear for while. To make progress, we need more data!
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- From the phenomenological point of view, the implications of NP explanations of $R_{D(*)}$ have been clear for while. To make progress, **we need more data!**

Thanks a lot for your attention!
Backup Slides
High-energy searches: $U_1$ leptoquark model (LH)

- The LHC is already probing the preferred region for the $U_1$ leptoquark model! CMS has a $3\sigma$ excess, ATLAS just set weaker than expected limits……too soon to say.

**$U_1$ pair production**

$$pp \rightarrow U^+_1U^-_1 \rightarrow b\tau^+\bar{t}\nu$$

$$\mathcal{B}(U_1 \rightarrow b\tau^+) \approx 0.5$$

**Drell-Yan t-channel exchange: $\tau\tau$**

$$b \rightarrow c\tau\nu$$

$\Lambda_{NP} \gtrsim 1.1$ TeV (ATLAS)

$|\beta_R| = 0$

Updated 90% CL region preferred by low-energy $b \rightarrow c\tau\nu$ data 2210.13422

High mass Drell-Yan tails

QCD corrections: [U. Haisch, L. Schnell, S. Schulte, 2209.12780]

[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, 2210.13422]
High-energy searches: $U_1$ leptoquark model (L&R)

- $U_1$ leptoquark model w/ RH currents preferred region fully within the HL-LHC reach!

\[ \mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[ (\bar{q}_L \gamma_\mu \ell_L^3) + \beta_R^{b\tau} (\bar{b}_R \gamma_\mu \tau_R) \right] \quad (\beta_R^{b\tau} = -1) \]

- Additional contributions give stronger bound from t-channel Drell-Yan $\tau\tau$:

\[ b_L \quad \tau_L + b_R \quad \tau_R \quad + \quad b_L \quad \tau_L + b_R \quad \tau_R \]

Updated 90% CL region preferred by low-energy $b \to c\tau\nu$ data 2210.13422

\[ |\beta_R| = 1 \]

[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, 2210.13422]
The low-energy $b \rightarrow c\tau\nu$ effective Lagrangian

$$\mathcal{L}^{b\rightarrow c\tau\nu}_{\text{eff}} = -\frac{2V_{cb}}{v^2} \left[ (1 + C_{V_L})(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L) + C_{V_R}(\bar{c}_R\gamma_\mu b_R)(\bar{\tau}_L\gamma_\mu\nu_L) \\
+ C_{S_L}(\bar{c}_R b_L)(\bar{\tau}_R\nu_L) + C_{S_R}(\bar{c}_L b_R)(\bar{\tau}_R\nu_L) + C_T(\bar{c}_R\sigma_{\mu\nu} b_L)(\bar{\tau}_R\sigma^{\mu\nu}\nu_L) \right] + \text{h.c.}$$

Vector LQ:

$U_1^{\mu} : C_{V_L}, C_{S_R}$

Scalar LQs:

$R_2 : C_{S_L} = 4C_T$

$S_1 : C_{V_L}, C_{S_L} = -4C_T$

$R_2 : C_{S_L} = 4C_T$

$$\delta R_D = +7.1 \text{Re}(C_T) + 17.2 |C_T|^2$$

$$\delta R_D^* = -5.6 \text{Re}(C_T) + 16.7 |C_T|^2$$

- This relation predicts opposite sign in $R_D$ vs $R_D^*$ due to interference with the SM.

- Since interference always goes as the real part, can make the WC’s purely imaginary and then do $R_D^{(*)}$ with NP squared.

- But then we need big WC’s: tension with high-$p_T$ and EW precision observables.
Neutral-current B-anomalies
The $b \rightarrow s \ell \ell$ anomalies before

- Until recently, two “types” of anomalies in $b \rightarrow sll$:
  1. $\mu/e$ universality ratios in $B \rightarrow K^{(*)}ll$
  2. discrepancies in obs. with muons only
     \begin{align*}
     \text{ang. obs. in } & B^{(0,+)} \rightarrow K^{*(0,+)}\mu^+\mu^- \\
     \text{BRs of } & B \rightarrow K\mu^+\mu^-, B \rightarrow K^*\mu^+\mu^-, B_s \rightarrow \phi\mu^+\mu^-
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\]

- 12/2022: a second LHCb analysis of $R_K$ & $R_{K^*}$ establishes $\mu/e$ lepton flavor universality in $b \to s\ell\ell$ at $\sim 5\%$ level

[compilation of $b \to s\mu\mu$ clean observables as of Dec. 2022 (©David Marzocca)]

\[
\begin{align*}
\text{low-}q^2 \left \{ 
R_K &= 0.994^{+0.090}_{-0.082} \text{ (stat)}^{+0.029}_{-0.027} \text{ (syst)}, \\
R_{K^*} &= 0.927^{+0.093}_{-0.087} \text{ (stat)}^{+0.036}_{-0.035} \text{ (syst)}, \\
\right. \\
\text{central-}q^2 \left \{ 
R_K &= 0.949^{+0.042}_{-0.041} \text{ (stat)}^{+0.022}_{-0.022} \text{ (syst)}, \\
R_{K^*} &= 1.027^{+0.072}_{-0.068} \text{ (stat)}^{+0.027}_{-0.026} \text{ (syst)}, \\
\right.
\end{align*}
\]
The $b \rightarrow s \ell \ell$ anomalies before

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[Ben A. Stefanek | 11th Edition of the LHC-Physics Conference, Belgrade]

- Still room for small $\mu/e$ lepton flavor violation at the $\sim 10\%$ level
The $b \rightarrow s \ell \ell$ anomalies after

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i O_i$$

$$O_{9}^{bs\mu\mu} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu} \gamma^\mu \mu)$$

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- Assuming NP in muons only, there's now tension between LFU ratios $R_{K^{(*)}}$ and BR's + $P'_5$
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- A flavor universal shift in $C_9$ is now sufficient to account for all $b \rightarrow s \mu \mu$ measurements: LFUV component in muons only is now compatible with zero.
The $b \to s\ell\ell$ anomalies after

\[ \mathcal{L}_{\text{eff}} = - \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i c_i O_i \]

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* But, non-trivial to distinguish from long-distance QCD ("charming penguins")

To understand these contributions better:

- Improvement on theory side [Gubernari et al. 2206.03797, Ciuchini et al. 2212.10516]
What changed? Implications for model building

\[ \mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i O_i \]

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\[ O_{9}^{bs\mu\mu} = (\bar{s}_L \gamma_{\mu} b_L)(\bar{\mu} \gamma^n \mu) \quad O_{10}^{bs\mu\mu} = (\bar{s}_L \gamma_{\mu} b_L)(\bar{\mu} \gamma^n \gamma_5 \mu) \]

\[ \mathcal{L}_{\text{eff}} = -4G_F \left( V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i O_i \right) \]

\[ \Delta C_9 = -C_{10}^{bs\mu\mu} \]
What changed? Implications for model building

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- Old models for combined explanation of \( R_D^{(*)} \) and \( R_K^{(*)} \) now must be \( \mu/e \) universal at the \( \sim 10 \% \) level. This is not difficult to achieve. The main consequence: LFV effects now predicted to be small (e.g. \( B \to K\tau\mu \), \( B_s \to \tau\mu \), \( \tau \to \mu X \) w/ \( X = \ell\ell^\prime, \phi, \gamma \))

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- Still interesting to consider models for \( R_{D(*)} \) (unaffected) that also give flavor universal contributions to the \( b \to s \ell \ell \) system.
Connection: $b \rightarrow c\tau\nu$ and universal $b \rightarrow s\ell\ell$

- Some vector semi-leptons that explain the charged-current anomalies give a flavor universal effect in $b \rightarrow s\ell\ell$ via RGE:

\[
\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i^\ell O_i^\ell
\]

\[
O_9^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell} \gamma^\mu \ell)
\]

- Leading-log running in SM gauge couplings gives

\[
\Delta C_9^U = \frac{v_{\text{EW}}^2}{3 V_{tb} V_{ts}^*} \left( [C_{lq}^{(3)}]_{\alpha\alpha 23} + [C_{lq}^{(1)}]_{\alpha\alpha 23} + [C_{qe}]_{23\alpha\alpha} \right) \log \left( \frac{m_b^2}{M^2} \right)
\]

*In general, sum over lepton flavors $\alpha$. For third-family NP, we take just $\alpha = 3$.  

[Bobeth, Haisch, 1109.1826; Crivellin et al., 1807.02068; Algueró et al., 1809.08447]
Connection: $b \rightarrow c \tau \nu$ and universal $b \rightarrow s \ell \ell$

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<td>Only $[C_{qe}]_{3333}$</td>
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*With both $[C_{qe}]_{3333}$ & $[C_{qe}]_{2333}$ active

[Bobeth, Haisch, 1109.1826; Crivellin et al., 1807.02068; Algueró et al., 1809.08447]
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$U_1$ connects $R_{D(*)}$ to $b \to s\tau\tau$ observables

- We have tree-level effects in $b \to s\tau\tau$ connected to the size of $R_{D(*)}$

- Since $b \to s\tau\tau$ is a FCNC, it is a 1-loop process in the SM. We therefore expect a huge NP enhancement in $b \to s\tau\tau$!

\[
\mathcal{B}(B \to K^{(*)}\tau\tau) / \mathcal{B}(B \to K^{(*)}\tau\tau)_{SM} \sim 16\pi^2 \frac{R_{D(*)}}{R_{D(*)}^{SM}}
\]
$U_1$ connects $R_{D(*)}$ to $b \to s\tau\tau$ observables

- We have tree-level effects in $b \to s\tau\tau$ connected to the size of $R_{D(*)}$

Updated 90% CL region preferred by low-energy $b \to c\tau\nu$ data [2210.13422]

[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, 2210.13422]
$U_1$ connects $R_D^{(*)}$ to universal $b \to s\ell\ell$ observables

- Large $b \to s\tau\tau$ implies a sizable flavor universal loop effect in $b \to s\ell\ell$!

Updated 90% CL region preferred by low-energy $b \to c\tau
\nu$ data \[\text{2210.13422}\]

$\Delta C_9^U = C_9^U - C_9^{\text{SM}}$

"Dirty" $b \to s\ell^+\ell^-$ data prefers:

$\Delta C_9^U \approx 0.75 \pm 0.25$

[Altmannshofer, Stangl 2103.13370
Bobeth, Haisch, 1109.1826; Crivellin et al., 1807.02068;
Algueró et al., 1809.08447]

\[\text{Ben A. Stefanek | 11th Edition of the LHC-Physics Conference, Belgrade}\]
Important 1-loop effects: $B \rightarrow K^{(*)}\nu\nu$ (4321 Model)

- Some (important) effects appear only at one loop. For $U_1$, requires UV model!

---

Updated 90% CL region preferred by low-energy $b \rightarrow c\tau\nu$ data 2210.13422

---

2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.00 0.05 0.10 0.15 0.20 0.25

$\delta R_{D^*}$

---

$B(B \rightarrow K^{(*)}\nu\nu)/B(B \rightarrow K^{(*)}\nu\nu)_{SM}$

---

$10^5 \times \text{Br}(B^+ \rightarrow K^+ \nu\bar{\nu})$

---

Updated 90% CL region preferred by low-energy $b \rightarrow c\tau\nu$ data 2210.13422

---

Belle II (63 fb$^{-1}$, Inclusive) 1.9±0.5% This work, preliminary

Belle (711 fb$^{-1}$, SL) 1.0±0.6% PRD96, 091101

Belle (711 fb$^{-1}$, Had) 0.8±0.7% PRD87, 111205

Babar (429 fb$^{-1}$, Had+SL) 0.8±0.7% PRD87, 111205

[Belle II Collaboration, 2104.12624]

[Fuentes-Martin, Isidori, König, Selimovic, 2009.11296]
Wrapping Up

Overview of ongoing LFU measurements

<table>
<thead>
<tr>
<th>mode</th>
<th>Run 1: 3 fb⁻¹ at 7/8 TeV</th>
<th>Run 2: 6 fb⁻¹ at 13 TeV</th>
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<tr>
<td></td>
<td>muonic</td>
<td>hadronic</td>
</tr>
<tr>
<td>(R(D^+))</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>(R(D^0))</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>(R(D^*))</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(R(\Lambda_c))</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>(R(\Lambda_c^+))</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>(R(J/\phi))</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>(R(D_s^+))</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>(R(D_{s^*}^+))</td>
<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>

- So far only published Run 1 results; Run 2 has four times as much data
- Many analyses in progress; no timelines
- Work ongoing also in \(b \rightarrow u\) sector; and excited states: \(R(D^{**}), R(D_{s}^{**})\)

- Also all of these processes yet to be analyzed (or only Run 1 data). Since the underlying partonic \(b \rightarrow c\tau\nu\) process is the same, NP expected in all of these!
The low-energy $b \to c\tau\nu$ effective Lagrangian

$$\mathcal{L}_{\text{eff}}^{b\to c\tau\nu} = -\frac{2V_{cb}}{v^2} \left[ (1 + C_{V_L})(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L) + C_{V_R}(\bar{c}_R \gamma_\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_L) + C_{S_L}(\bar{c}_R b_L)(\bar{\tau}_R \nu_L) + C_{S_R}(\bar{c}_L b_R)(\bar{\tau}_R \nu_L) + C_T(\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu} \nu_L) \right] + \text{h.c.}$$

**SMEFT-LEFT Matching:**

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<td>$[C_{lq}^{(1)}]_{\alpha\beta ij}^{\nu}$</td>
<td>$\frac{1}{4} [y^L]<em>{i\alpha} [y^L]</em>{j\beta}^*$</td>
<td>$-\frac{1}{2} [x^L]<em>{i\beta} [x^L]</em>{j\alpha}^*$</td>
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<td>$[C_{lq}^{(3)}]_{\alpha\beta ij}^{\nu}$</td>
<td>$-\frac{1}{4} [y^L]<em>{i\alpha} [y^L]</em>{j\beta}^*$</td>
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<tr>
<td>$[C_{ledq}]_{\alpha\beta ij}^{\nu}$</td>
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**Vector LQ:**

$U_1^\mu : C_{V_L}, C_{S_R}$

**Scalar LQs:**

$R_2 : C_{S_L} = 4C_T$

$S_1 : C_{V_L}, C_{S_L} = -4C_T$

[L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari, F. Wilsch, 2207.10714]
The low-energy $b \to c\tau\nu$ effective Lagrangian

$$\mathcal{L}_{b\to c\tau\nu}^b = -\frac{2V_{cb}}{v^2} \left[ (1 + C_{VL})(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma_\mu \nu_L) + C_{VR}(\bar{c}_R\gamma_\mu b_R)(\bar{\tau}_L\gamma_\mu \nu_L) 
+ C_{SL}(\bar{c}_R b_L)(\bar{\tau}_R \nu_L) + C_{SR}(\bar{c}_L b_R)(\bar{\tau}_R \nu_L) + C_T(\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu} \nu_L) \right] + \text{h.c.}$$

SMFT-LEFT Matching:

SM  $C_{VL} = -v^2 \sum_i \frac{V_{2i}}{V_{23}} [C_{\text{Hud}}^{(3)}]_{i3i3}$,

$C_{VR} = \frac{v^2}{2V_{23}} [C_{\text{Hud}}^{(3)}]_{23}$,

$C_{SL} = -\frac{v^2}{2V_{23}} [C_{\text{lequ}}^{(1)}]_{3333}$,

$C_{SR} = -\frac{v^2}{2} \sum_{i=1}^3 \frac{V_{2i}^*}{V_{23}} [C_{\text{ledq}}^{(3)}]_{333i}$,

$C_T = -\frac{v^2}{2V_{23}} [C_{\text{lequ}}^{(3)}]_{3332}$.

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SMEFT-LEFT Matching:

$$\begin{align*}
C_{V_L} &= -v^2 \sum_i \frac{V_{2i}}{V_{23}} [\mathcal{C}_l^{(3)}]_{33i3}, \\
C_{V_R} &= \frac{v^2}{2V_{23}} [\mathcal{C}_{\text{HuId}}^{(3)}]_{23}, \\
C_{S_L} &= -\frac{v^2}{2V_{23}} [\mathcal{C}_{\text{equ}}^{(1)}]_{3332}, \\
C_{S_R} &= -\frac{v^2}{2} \sum_{i=1}^3 \frac{V_{2i}^*}{V_{23}} [\mathcal{C}_{\text{equ}}^{(3)}]_{333i}, \\
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\end{align*}$$

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$$+ \left. C_{S_L}(\bar{c}_R b_L)(\bar{\tau}_R \nu_L) + C_{S_R}(\bar{c}_L b_R)(\bar{\tau}_R \nu_L) + C_T(\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu} \nu_L) \right] + \text{h.c.}$$

SMEFT-LEFT Matching:

$$C_{V_L} = -v^2 \sum_i \frac{V_{2i}}{V_{23}} \left[ C^{(3)}_{lq} \right]_{3i3}^3,$$

$$C_{V_R} = \frac{v^2}{2V_{23}} \left[ C^{(3)}_{Hu,d} \right]_{23},$$

$$C_{S_L} = -\frac{v^2}{2V_{23}} \left[ C^{(1)}_{\text{ledq}} \right]_{3i33}^3,$$

$$C_{S_R} = -\frac{v^2}{2} \sum_{i=1}^3 \frac{V_{2i}^*}{V_{23}} \left[ C^{(1)}_{\text{ledq}} \right]_{3i33}^3,$$

$$C_T = \frac{v^2}{2V_{23}} \left[ C^{(3)}_{\text{ledq}} \right]_{3i33}^3.$$
Updated $S_1, R_2, U_1$ fits to data w/ following observables

- Data from low-energy $b \rightarrow c\tau\nu$ transitions

$$R_D, R_{D^*}, R_{\Lambda_c}$$

- $\tau$-decays and EW precision observables (EWPO) [ LL running in $y_t, g_L, g_Y$ ]

$$Z + W \text{ pole observables } + \text{ LFU tests in } \tau\text{-decays: } g^\tau_W/g^e_W$$

[L. Allwicher, G. Isidori, J. M. Lizana, N. Selimovic, BAS, 2302.11584]

- Data from high-$p_T$ searches at the collider: di-tau $\tau\tau$ and mono-tau $\tau + E_T$

\[\text{[L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari, F. Wilsch, 2207.10756]}\]
Simplified $S_1$ scalar LQ model and fit

\[ \mathcal{L} \supset \lambda_L^{b\nu} \bar{q}_L^c e_L^3 S_1 + \lambda_R^{c\tau} \bar{c}_R^c \tau_R S_1 \]
Simplified $R_2$ scalar LQ model and fit

\[ \mathcal{L} \supset \lambda^b_{L} \bar{q}^3_{L} R_2 \tau_R - \lambda^c_{R} \bar{c}_R R_2 \epsilon^3_{L} \]
Simplified $U_1$ vector LQ model and fit

\[ \mathcal{L} \supset \left( g_L^{b\tau} \bar{q}_L^3 \gamma_\mu \ell_L^3 + g_L^{s\tau} \bar{q}_L^2 \gamma_\mu \ell_L^3 \right) U_1^\mu \]
U(2)-like new physics in $b \rightarrow c\tau\nu$ decays

- Actually, following the U(2) hypothesis, we should have:

\[
\mathcal{A}_{NP}^{33} \sim \frac{1}{\Lambda_{NP}^2} + \mathcal{A}_{NP}^{23} \sim \frac{V_q}{\Lambda_{NP}^2}
\]

\[
\mathcal{A}_{NP}(b \rightarrow c\tau\nu) = V_{cb}\mathcal{A}_{NP}^{33} + V_{cs}\mathcal{A}_{NP}^{23}
\]

**Flavor conserving**

\[
b_L \xrightarrow{t_L} \tau_L \nu_L
\]

**Flavor violating**

\[
b_L \xrightarrow{c_L} \tau_L \nu_L
\]
U(2)-like new physics in $b \rightarrow c\tau\nu$ decays

- Actually, following the U(2) hypothesis, we should have:

\[
\mathcal{A}^{33}_{NP} \sim \frac{1}{\Lambda_{NP}^2} + \mathcal{A}^{23}_{NP} \sim \frac{V_q}{\Lambda_{NP}^2}
\]

\[
\mathcal{A}_{NP}(b \rightarrow c\tau\nu) = V_{cb}\mathcal{A}^{33}_{NP} + V_{cs}\mathcal{A}^{23}_{NP}
\]

- U(2) suppressed flavor violation means we need an even lower NP scale!

\[
2 \frac{\mathcal{A}_{NP}}{\mathcal{A}_{SM}} \approx \frac{v^2}{\Lambda_{NP}^2} \left(1 + \frac{V_q}{V_{cb}}\right) \approx \delta R_{D^*} \quad \Rightarrow \quad \Lambda_{NP} \approx 1.3 \text{ TeV} \left(\frac{0.12}{\delta R_{D^*}}\right)^{1/2}
\]

(V_q = 0.1)
A final comment on $R_{K^*}$

- 12/2022: a second LHCb analysis of $R_K$ & $R_{K^*}$ establishes $\mu/e$ lepton flavor universality in $b \to s ll$ at $\sim 5\%$ level [LHCb,221209152]

[compilation of $b \to s \mu\mu$ clean observables as of Dec. 2022 (©David Marzocca)]

\[
\begin{align*}
\text{low-}q^2 & \quad \begin{cases} 
R_K &= 0.994_{-0.082}^{+0.090} \text{ (stat)}_{-0.027}^{+0.029} \text{ (syst)}, \\
R_{K^*} &= 0.927_{-0.087}^{+0.093} \text{ (stat)}_{-0.035}^{+0.036} \text{ (syst)},
\end{cases} \\
\text{central-}q^2 & \quad \begin{cases} 
R_K &= 0.949_{-0.041}^{+0.042} \text{ (stat)}_{-0.022}^{+0.022} \text{ (syst)}, \\
R_{K^*} &= 1.027_{-0.068}^{+0.072} \text{ (stat)}_{-0.026}^{+0.027} \text{ (syst)}.
\end{cases}
\end{align*}
\]

- Still room for small $\mu/e$ lepton flavor violation at the $\sim 10\%$ level
A final comment on $R_K^{(*)}$

- 12/2022: a second LHCb analysis of $R_K$ & $R_{K^*}$ establishes $\mu/e$ lepton flavor universality in $b \to sll$ at $\sim 5\%$ level

$$[\text{LHCb},221209152]$$

[ compilation of $b \to s\mu\mu$ clean observables as of Dec. 2022 (©David Marzocca)]

- Still room for small $\mu/e$ lepton flavor violation at the $\sim 10\%$ level

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} U^\mu V_q \left[ (\bar{q}_L)_{\gamma \mu \ell_L}^2 + \beta^{\ast t}_{st} (\bar{q}_L)_{\gamma \mu \ell_L}^2 + \beta^{b\mu}_{bt} (\bar{q}_L)_{\gamma \mu \ell_L}^2 + \beta^{s\mu}_{bt} (\bar{q}_L)_{\gamma \mu \ell_L}^2 \right]$$

Nothing changes here, still calls for light NP!

$$\frac{V_q V_\ell}{U(2)_\ell \text{ breaking } V_q}$$

$R_D^{(*)}$

$R_K^{(*)}$ is simply smaller now.