Mostly Leptoquarks and some VL Fermions

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11th Edition of the LHC-Physics Conference
Metropol Palace, Belgrade, Serbia
May 23rd, 2023
Anomalies in $b \rightarrow c$ semi-leptonics: $R_D$ and $R_{D^*}$

\[ R_{D(*)} = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \rightarrow D^{(*)}\ell\bar{\nu})} \]
\[ \ell = e, \mu \]

- Theoretically semi-clean. Measurements by Babar, Belle, LHCb in good agreement.

- Enhancement of $\sim 10\%$ over SM due to excess in tau mode: $B \rightarrow D^{(*)}\tau\bar{\nu}_\tau$.

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

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 physics in $b \rightarrow c\tau\nu$ decays

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

\[ \mathcal{A}_{\text{SM}} \sim \frac{g_L^2 V_{cb}}{2M_W^2} = \frac{2V_{cb}}{\nu^2} \]

SM process

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

Heavy new physics

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

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

- LH NP $\Rightarrow b \rightarrow s\tau(\nu\nu)$ 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 $\Rightarrow b \to s\tau(\nu\nu)$ couplings. LQ's have two important advantages.

1. $\Delta F = 2$:

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>
<td>(S_1 = (3, 1)_{-1/3})</td>
<td>X</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>(R_2 = (3, 2)_{7/6})</td>
<td>X</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>(\tilde{R}<em>2 = (3, 2)</em>{1/6})</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>(S_3 = (3, 3)_{-1/3})</td>
<td>✓</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>(U_1 = (3, 1)_{2/3})</td>
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<td>X</td>
</tr>
</tbody>
</table>

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

Vector Leptoquarks:
- \(\star U_1 \sim (3, 1, 2/3)\) (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?

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

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

  \[
  \begin{align*}
  b_L & \quad \tau_L \\
  c_L & \quad \nu_L \\
  & \quad \Rightarrow \\
  S_{U(2)}_L & \\
  & \quad \Rightarrow \\
  b_L & \quad \tau_L \\
  s_L & \quad \tau_L \\
  & \quad \Rightarrow \\
  \Delta C_9^U = C_9^U - C_9^{SM}
  \end{align*}
  \]

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

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

\[ U(2)_q\text{-breaking} \sim O(V_{cb}) \]
Simplified model for $U_1$ leptoquark

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

Integrate out the $U_1$ LQ:

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

RUNNING to EW SCALE + MATCHING

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

Low-energy WC's ↔ Model parameters:

$$C_{LL}^c = \frac{g_U^2 v^2}{4M_U^2} \left(1 + \frac{V_{cs}}{V_{cb}} \beta_L^{s\tau}\right),$$

$$C_{LR}^c = \beta_R^{b\tau*} C_{LL}^c$$
Low-energy fit for $U_1$ leptoquark model

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

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

$$\delta R_D^{(*)} \approx 2 C_{\text{LL}}^c - a_D^{(*)} C_{\text{LR}}^c \quad \begin{cases} 
    a_D \approx 3.00 \\
    a_{D^*} \approx 0.24
\end{cases}$$

Low-energy WC's ↔ Model parameters

$$C_{\text{LL}}^c = \frac{g_\text{U} v^2}{4 M_U^2} \left( 1 + \frac{V_{cs}}{V_{cb}} \beta_L^{s_2} \right), \quad C_{\text{LR}}^c = \beta_R^{b_2^*} C_{\text{LL}}^c$$

[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, 2210.13422]
Low-energy fit for $U_1$ leptoquark model

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

$$\delta R_D^{(*)} \approx 2 C_{LL}^c - a_D^{(*)} C_{LR}^c$$ \hspace{1cm} \{ \begin{align*}
a_D & \approx 3.00 \\
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\end{align*} \}

Low-energy WC's ↔ Model parameters

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

Matching: NP scale and U(2)-breaking

$$\frac{1}{\Lambda_{NP}^2} = \frac{g_U^2}{2 M_U^2}, \quad V_q = \beta_{s}^{st}$$

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

ATLAS Preliminary

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

Excludes CMS' excess
UV Completion for the $U_1$ Leptoquark
UV Model: New flavor non-universal gauge interactions

Based on “4321” gauge symmetry:

\[
SU(4)_h \times SU(3)_l \times SU(2)_L \times U(1)_{l+R} \xrightarrow{\Omega_{1,3,15}} \Theta(\text{TeV}) \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y + U_1, G', Z'
\]
UV Model: New flavor non-universal gauge interactions

Based on "4321" gauge symmetry:

\[ SU(4) \sim G^a \oplus U^a \]

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

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

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

\[ \psi_L \sim \begin{pmatrix} q^3_L \\ \ell^3_L \end{pmatrix} \quad \psi^+_R \sim \begin{pmatrix} u^3_R \\ \nu^3_R \end{pmatrix} \quad \psi^-_R \sim \begin{pmatrix} d^3_R \\ e^3_R \end{pmatrix} \]

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

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\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^3_{L,R} \\ L^3_{L,R} \end{pmatrix}
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\[ \psi_L \sim \left( q_L^3 \right) \quad \psi_R^+ \sim \left( u_R^3 \right) \quad \psi_R^- \sim \left( d_R^3 \right) \quad \chi_{L,R} \sim \left( Q_{L,R} \right) \]

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

\[ \mathcal{L}_{mix} \supset -\lambda_q \bar{q}_L^i \Omega_3 \chi_R - y_{\pm} \bar{\chi}_L H \Psi_R^\pm \quad \rightarrow \quad \frac{y_{\pm} \lambda_q^i}{M_{\chi}} \bar{q}_L^i \Omega_3 H \Psi_R^\pm \]

Diagram: \( \langle \Omega_3 \rangle \quad H \quad \bar{q}_L^i \quad Q_R \quad \bar{Q}_L \quad t_R/b_R \)
UV Model: Vector-like fermions

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\]

Vector-like Lepton:

- Controls loop FCNC's

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

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

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

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

\[ \psi_L \sim \left( q^3_L \ell^3_L \right) \quad \psi^+_R \sim \left( u^3_R \nu^3_R \right) \quad \psi^-_R \sim \left( d^3_R e^3_R \right) \quad \chi_{L,R} \sim \left( Q_L,R \right) \]

Vector-like Lepton:
- Controls loop FCNC's

Vector-like Quark:
- CKM mixing and effects in EWPO via RGE

\[ L_{\text{mix}} \supset -y_{\pm} \bar{\chi}_L H \Psi^\pm_R \]

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

[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.

$$\frac{\Delta m_W}{m_W} \supset -\frac{\nu^2}{4} \frac{g_L^2}{g_L^2 - g_Y^2} C_{HD}$$

$$\Theta_{HD} = |H^\dagger D_\mu H|^2$$

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

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

- The tension in the LFU ratios $R_{D(\ast)}$ 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 $R_{K(\ast)}$!

- Consistent picture, but present data in $b \rightarrow c\tau\nu$ 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 $b \rightarrow c\tau\nu$ transitions to flavor universal effects in the $b \rightarrow s\ell\ell$ 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 $R_{D(\ast)}$, such as an $\sim$50\% enhancement in $B \rightarrow K\nu\bar{\nu}$ and large positive shifts to the $W$-mass via RGE.

- From the phenomenological point of view, the implications of NP explanations of $R_{D(\ast)}$ have been clear for while. To make progress, we need more data!
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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 3σ excess, ATLAS just set weaker than expected limits……too soon to say.

$U_1$ pair production

\[ g \rightarrow U_1^+ + U_1^- \rightarrow b \tau^+ + t\bar{t} \]

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

$pp \rightarrow U_1^+ U_1^- \rightarrow b \tau^+ t\bar{t}$

[2012.0417]

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

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

$|\beta_R| = 0$

$M_U [\text{GeV}]$

Updated 90% CL region preferred by low-energy

$b \rightarrow c t\nu$ data [2210.13422]

[2002.1222]

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!

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

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

![Diagram of $\tau\tau$ processes]

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

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

**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 $b \to s \ell \ell$ anomalies before

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

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

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

\[ \begin{align*}
  \text{low-$q^2$} & \begin{cases} 
    R_K &= 0.994_{-0.082}^{+0.090} \text{ (stat)}_{-0.027}^{+0.029} \text{ (syst)}, \\
    R_{K^*} &= 0.927_{-0.087}^{+0.093} \text{ (stat)}_{-0.035}^{+0.036} \text{ (syst)},
  \end{cases} \\
  \text{central-$q^2$} & \begin{cases} 
    R_K &= 0.949_{-0.041}^{+0.042} \text{ (stat)}_{-0.022}^{+0.022} \text{ (syst)}, \\
    R_{K^*} &= 1.027_{-0.068}^{+0.072} \text{ (stat)}_{-0.026}^{+0.027} \text{ (syst)}.
  \end{cases}
\]
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\[
\begin{align*}
\text{low-}q^2 & \quad R_K = 0.994^{+0.090}_{-0.082} (\text{stat})^{+0.029}_{-0.027} (\text{syst}), \\
& \quad R_{K^*} = 0.927^{+0.093}_{-0.087} (\text{stat})^{+0.036}_{-0.035} (\text{syst}), \\
\text{central-}q^2 & \quad R_K = 0.949^{+0.042}_{-0.041} (\text{stat})^{+0.022}_{-0.020} (\text{syst}), \\
& \quad R_{K^*} = 1.027^{+0.072}_{-0.068} (\text{stat})^{+0.027}_{-0.026} (\text{syst}). \\
\end{align*}
\]

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

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

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

$$O_{10}^{bs\mu\mu} = (\bar{s}_L \gamma_{\mu} b_L)(\bar{\mu} \gamma^\mu \gamma_5 \mu)$$

- Assuming NP in muons only, there's now tension between LFU ratios $R_{K^{(*)}}$ and BR's + $P'_5$
The $b \rightarrow s\ell\ell$ anomalies after

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

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- Assuming NP in muons only, there's now tension between LFU ratios $R_{K^*(\mu)}$ and BR's + $P'_5$

- 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 $b \rightarrow s \ell \ell$ anomalies after

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

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

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

- Assuming NP in muons only, there's now tension between LFU ratios $R_{K^*}$ and BR's + $P'_5$

- 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.

* 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

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

- A **flavor universal shift** in \( C_9 \) is now sufficient to account for all \( b \to s\mu\mu \) measurements.

\[ O_9^{bs\mu\mu} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu} \gamma^\nu \mu) \quad O_{10}^{bs\mu\mu} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu} \gamma^\nu \gamma_5 \mu) \]

---

Ben A. Stefanek | 11th Edition of the LHC-Physics Conference, Belgrade
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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- A flavor universal shift in \( C_9 \) is now sufficient to account for all \( b \to s\mu\mu \) measurements.

- 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/ \( X = \ell\bar{\ell}, \phi, \gamma \))

[Flavio plot showing data points and theoretical predictions for different decay modes.]

[Reference: Greljo et al., 2212.10497]
What changed? Implications for model building

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

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

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- A flavor universal shift in \( C_9 \) is now sufficient to account for all \( b \rightarrow s\mu\mu \) measurements.

- 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. \( B \rightarrow K\tau\mu \), \( B_s \rightarrow \tau\mu \), \( \tau \rightarrow \mu X \) w/ \( X = \ell\bar{\ell}, \phi, \gamma \))

- Still interesting to consider models for \( R_D^{(*)} \) (unaffected) that also give flavor universal contributions to the \( b \rightarrow s\ell\ell \) system.

[flavio diagram]
Connection: $b \rightarrow c\tau\nu$ and universal $b \rightarrow s\ell\ell$

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

\[
\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i^\ell O_i^\ell = (s_L\gamma_\mu b_L)(\bar{\ell} \gamma^\mu \ell)
\]

- Leading-log running in SM gauge couplings gives

\[
\Delta C_9^U = \frac{v_{\text{EW}}^2}{3V_{tb}V_{ts}^*} \left( [C_{lq}^{(3)}]_{\alpha\alpha23} + [C_{lq}^{(1)}]_{\alpha\alpha23} + [C_{qe}]_{23\alpha\alpha} \right) \log \left( \frac{m_b^2}{M^2} \right)
\]

*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 $b \rightarrow s\ell\ell$

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

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

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

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

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$U_1$ connects $R_D^{(*)}$ to $b \rightarrow s\tau\tau$ observables

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

$$b_{L,R} \quad \tau_{L,R}$$

$U_1$

$c_L \quad \nu_L$

SU(2)$_L$ $\Rightarrow$

$b \rightarrow c\tau\nu$

$$b_{L,R} \quad \tau_{L,R}$$

$s_L \quad \tau_L$

$b \rightarrow s\tau\tau$

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

$$\frac{\mathcal{B}(B \rightarrow K^{(*)}\tau\tau)}{\mathcal{B}(B \rightarrow K^{(*)}\tau\tau)_{SM}} \sim 16\pi^2 \frac{R_D^{(*)}}{R_D^{SM}}$$

Ben A. Stefanek | 11th Edition of the LHC-Physics Conference, Belgrade
$U_1$ connects $R_{D(\ast)}$ to $b \to s\tau\tau$ observables

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

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

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

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

RGE

$$\Rightarrow$$

$\Delta C^U_9 = C^U_9 - C^\text{SM}_9$

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

$\Delta C^U_9 \approx 0.75 \pm 0.25$

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]

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

![Diagram showing the one-loop process $b \rightarrow c\nu\nu$]

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

![Graph showing the ratio $B(B \rightarrow K^{(*)}\nu\bar{\nu})/B(B\rightarrow K^{(*)}\nu\tilde{\nu})_{SM}$ vs. $\delta R_{D^*}$]

[Belle II Collaboration, 2104.12624]

[Fuentes-Martín, 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>
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<tr>
<td>$R(D^+)$</td>
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<td>X</td>
</tr>
<tr>
<td>$R(D^0)$</td>
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<td>X</td>
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<tr>
<td>$R(D^*)$</td>
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<tr>
<td>$R(J/\phi)$</td>
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<td></td>
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<tr>
<td>$R(D_{s}^+)$</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>$R(D_{s}^{*+})$</td>
<td>X</td>
<td></td>
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</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 $b \to u$ sector; and excited states: $\mathcal{R}(D^{**}), \mathcal{R}(D_s^{**})$

Suzanne Klaver  | LFU in charged-current $b$ decays | Implication WS | 19 October 2022 | 18

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

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

SMEFT-LEFT Matching:

SM

$$C_{V_L} = -v^2 \sum_i \frac{V_{2i}}{V_{23}} [C^{(3)}_{lq}]_{33i 3}^3,$$

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

$$C_{S_L} = -\frac{v^2}{2V_{23}} [C^{(1)}_{lequ}]_{3332}^3,$$

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

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

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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

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

**SMEFT-LEFT Matching:**

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+ 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) \left. \right] + \text{h.c.} \]

SMEFT-LEFT Matching:

\[ SM \]
\[ C_{V_L} = -v^2 \sum_i \frac{V_{2i}^2}{V_{23}} [c_{lq}^{(3)}]_{333i} \]
\[ C_{V_R} = \frac{v^2}{2V_{23}} [c_{Hud}^{(3)}]_{23} \]
\[ C_{S_L} = -\frac{v^2}{2V_{23}} [c_{lequ}^{(1)}]_{333i}^* \]
\[ C_{S_R} = -\frac{v^2}{2} \sum_{i=1}^3 \frac{V_{2i}^2}{V_{23}} [c_{leq}^{(1)}]_{333i}^* \]
\[ C_T = -\frac{v^2}{2V_{23}} [c_{lequ}^{(3)}]_{3333}^* \]

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</tr>
<tr>
<td>$[c_{lequ}^{(3)}]_{\alpha\beta ij}$</td>
<td>$-\frac{1}{8} [y_{L}^I]<em>{i\alpha} [y</em>{R}^I]_{j\beta}$</td>
<td>$-\frac{1}{8} [y_{R}^I]<em>{i\beta} [y</em>{L}^I]_{j\alpha}$</td>
<td>-</td>
</tr>
</tbody>
</table>

**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

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

**SMEFT-LEFT Matching:**

<table>
<thead>
<tr>
<th>Field</th>
<th>$S_1$</th>
<th>$R_2$</th>
<th>$U_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum Numbers</td>
<td>$(3, 1, 1/3)$</td>
<td>$(3, 2, 7/6)$</td>
<td>$(3, 1, 2/3)$</td>
</tr>
<tr>
<td>$C_{V_L}$</td>
<td>$\frac{1}{4}[y_{1}^{R}]<em>{i\alpha}[y</em>{j}^{R}]_{j\beta}$</td>
<td>$-\frac{1}{2}[x_{1}^{L}]<em>{i\beta}[x</em>{j}^{L}]_{j\alpha}$</td>
<td></td>
</tr>
<tr>
<td>$C_{V_R}$</td>
<td>$-\frac{1}{4}[y_{1}^{L}]<em>{i\alpha}[y</em>{j}^{L}]_{j\beta}$</td>
<td>$-\frac{1}{2}[x_{1}^{L}]<em>{i\beta}[x</em>{j}^{L}]_{j\alpha}$</td>
<td></td>
</tr>
<tr>
<td>$C_{S_L}$</td>
<td>$[C_{leq}^{(1)}]_{\alpha \beta ij}$</td>
<td>$-\frac{1}{2}[y_{2}^{L}]<em>{i\beta}[y</em>{j}^{L}]_{j\alpha}$</td>
<td>$-\frac{1}{2}[y_{2}^{R}]<em>{i\beta}[y</em>{j}^{L}]_{j\alpha}$</td>
</tr>
<tr>
<td>$C_{S_R}$</td>
<td>$[C_{leq}^{(3)}]_{\alpha \beta ij}$</td>
<td>$-\frac{1}{8}[y_{1}^{L}]<em>{i\alpha}[y</em>{j}^{L}]_{j\beta}$</td>
<td>$-\frac{1}{8}[y_{1}^{R}]<em>{i\beta}[y</em>{j}^{L}]_{j\alpha}$</td>
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[L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari, F. Wilsch, 2207.10714]
Updated $S_1, R_2, U_1$ fits to data w/ following observables

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

\[ R_D, R_{D^*}, R_{\Lambda_c} \]

[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, 2210.13422]

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

\[ Z + W \text{ pole observables} + \text{LFU tests in } \tau\text{-decays: } g_W^\tau/g_W^e \]

[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 $\tau + E_T$

[HighPT]

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

$$\mathcal{L} \supset \lambda_L^{bu} \bar{q}_L^c e_L^c \ell_L^3 S_1 + \lambda_R^{ct} \bar{c}_R^c \tau_R S_1$$
Simplified $R_2$ scalar LQ model and fit

$$\mathcal{L} \supset \lambda_L^{b\tau} \bar{q}_L^3 R_2 \tau_R - \lambda_R^{c\nu} \bar{c}_R R_2 \epsilon \ell_L^3$$
Simplified $U_1$ vector LQ model and fit

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

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

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

\[ \mathcal{A}_{NP}(b \rightarrow c\tau\nu) = V_{cb} \mathcal{A}_{NP}^{33} + V_{cs} \mathcal{A}_{NP}^{23} \]
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- Actually, following the U(2) hypothesis, we should have:

**Flavor conserving**

\[ A_{NP}^{33} \sim \frac{1}{\Lambda_{NP}^2} \]

**Flavor violating**

\[ A_{NP}^{23} \sim \frac{V_q}{\Lambda_{NP}^2} \]

\[ A_{NP}(b \to c\tau\nu) = V_{cb}A_{NP}^{33} + V_{cs}A_{NP}^{23} \]

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

\[ 2 \frac{A_{NP}}{A_{SM}} \approx \frac{v^2}{\Lambda_{NP}^2} \left(1 + \frac{V_q}{V_{cb}}\right) \approx \delta R_{D^*} \]

\[ \Lambda_{NP} \approx 1.3 \text{ TeV} \left(\frac{0.12}{\delta R_{D^*}}\right)^{1/2} \]

\[ (V_q = 0.1) \]
A final comment on $R_K^\ast$ (*)

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

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

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

- 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 $b \rightarrow s l l$ at $\sim 5\%$ level [LHCb,221209152]

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

```
\begin{align*}
\mathcal{L} & \supset \frac{g_U}{\sqrt{2}} U_{11}^{\mu} \left[ (\bar{q}_L^3 \gamma_\mu \ell_L^3) + \beta^{st}_L (\bar{q}_L^2 \gamma_\mu \ell_L^2) + \beta^{bu}_L (\bar{q}_L^3 \gamma_\mu \ell_L^3) + \beta^{su}_L (\bar{q}_L^2 \gamma_\mu \ell_L^2) \right] \\
\end{align*}
```

U(2)-breaking parameter:

- $V_q$
- $V_\ell$
- $V_q V_\ell$

Nothing changes here, still calls for light NP!

$U(2)_\ell$ breaking $V_\ell$ is simply smaller now.