$b \rightarrow c \tau \bar{\nu}_{e,\mu}$ contributions to $R(D^{(*)})$

Shikma Bressler, Federico De Vito Halevy and Yosef Nir

Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 7610001, Israel
E-mail: shikma.bressler@weizmann.ac.il, federico.devitohalevy@weizmann.ac.il, yosef.nir@weizmann.ac.il

Abstract: The $R(D^{(*)})$ puzzle stands for a $\sim 3\sigma$ violation of lepton flavor universality between the decay rates of $B \rightarrow D^{(*)}\tau\nu$ and $B \rightarrow D^{(*)}\ell\nu$, where $\ell = e, \mu$. If it is accounted for by new physics, there is no reason in general that the relevant neutrinos are, respectively, $\nu_\tau$ and $\nu_\ell$. We study whether the $\tau$ related rate could be enhanced by significant contributions to $B \rightarrow D^{(*)}\tau\nu_\ell$ from a class of operators in the Standard Model Effective Field Theory (SMEFT). We find the upper bounds from forbidden or rare meson decays imply that the contributions from the lepton flavor violating processes account for no more than about 4% of the required shift. Yet, no fine-tuned flavor alignment is required for the new physics. Searching for the related high-$p_T$ process $pp \rightarrow \tau^+\tau^-$ can at present put a lower bound on the scale of the lepton flavor violating new physics that is a factor of 2.2 weaker than the bound from meson decays. An exception to our conclusion arises from a specific combination of scalar and tensor SMEFT operators.

Keywords: Semi-Leptonic Decays, SMEFT, Specific BSM Phenomenology

ArXiv ePrint: 2201.11393
1 Introduction

Within the Standard Model (SM), the electroweak interactions of the leptons are flavor universal. Violation of lepton flavor universality arises from Yukawa interactions, that are negligible in this context, and from phase space effects, which are calculable. A test of the SM prediction of lepton flavor universality is provided by the ratios

\[ R(D^{(*)}) \equiv \frac{\Gamma(B \to D^{(*)} \tau\bar{\nu})}{\Gamma(B \to D^{(*)} \ell\bar{\nu})}, \quad (\ell = e \text{ or } \mu). \] (1.1)

The SM predictions, derived by naive averaging [1] over the results reported in refs. [2–5], are

\[ R(D) = 0.299 \pm 0.003, \]
\[ R(D^*) = 0.258 \pm 0.005. \] (1.2)

The current world averages for \( R(D) \) and \( R(D^*) \), combining the results reported in refs. [6–14] are as follows [1]:

\[ R(D) = 0.340 \pm 0.030, \]
\[ R(D^*) = 0.295 \pm 0.014. \] (1.3)

The difference of the experimental measurements from the SM predictions corresponds to about 3.1\( \sigma \) (p-value of \( 2.7 \times 10^{-3} \)). We thus aim to explain

\[ R(D^{(*)})/R(D^{(*)})^{\text{SM}} \approx 1.14 \pm 0.05. \] (1.4)

The quark transition via which the \( B \to D^{(*)} \tau\bar{\nu} \) proceeds is \( b \to c\tau\bar{\nu} \). Note, however, that the flavor of the neutrino is, of course, unobservable. It could be \( \nu_\tau \), in which case
the process respects the accidental lepton flavor symmetry of the SM. There is no reason,
however, that the symmetry is respected by new physics, particularly when the new physics
violates lepton flavor universality, so that the neutrino could also be $\nu_\mu$ or $\nu_e$ or some
combination of the three flavors. This possibility has been discussed very little in the
literature (for an exception, see [15]), and we aim to fill in this gap. We ask three main
questions:

- Could the $R(D^{(*)})$ puzzle be solved via new physics contributions to $b \to c \tau \nu_\ell$ with
  $\ell = e, \mu$?
- If not, how precise should the alignment of $\nu$ with $\nu_\tau$ be?
- What is the sensitivity of the high-$p_T$ experiments at the LHC to such lepton flavor
  violating new physics?

The plan of this paper is as follows. In section 2, we present the theoretical framework
of the SM effective field theory (SMEFT), within which we carry out our analysis,
and estimate the size of the dimension-six operators that can explain the $R(D^{(*)})$ puzzle.
In section 3, we obtain bounds on these operators from various processes to which they
contribute. In section 4 we explore the reach of current and future collider experiments to
probe the dimension-six terms with searches of lepton flavor violating di-lepton final states.
We summarize our conclusions in section 5. A discussion of additional operators is given
in appendix A.

2 $R(D^{(*)})$ in the SMEFT

We assume that the new physics contributions originate at a scale $\Lambda \gg v$, and consider the
following two terms in the SMEFT Lagrangian [15]:

$$
\mathcal{L}_{NP} = \frac{C_{ilk\ell m}}{\Lambda^2} (\bar{L}_i \gamma_{\sigma} L_l)(\bar{Q}_k \gamma^\sigma Q_m) + \frac{C_{ilk\ell m}}{\Lambda^2} (\bar{L}_i \gamma_{\sigma} \tau_a^\alpha L_l)(\bar{Q}_k \gamma^\sigma \tau_a^\alpha Q_m),
$$

(2.1)

where $L$ is the SU(2)-doublet lepton field, $Q$ is the SU(2)-doublet quark field, and $i, l, k, m$
are flavor indices. For the sake of definiteness, and to avoid the strongest constraints from
flavor changing neutral current (FCNC) processes, we take $i = \tau$, $k = s$, and $m = b$, while
$l$ runs over $e, \mu, \tau$. Three comments are in order concerning our choices for the flavor,
Lorentz and CP structures:

- The weakest constraints apply when $k = m = b$, in which case no FCNC in the down
  sector are generated. However, the contribution to the $b \to c \tau \bar{\nu}_\ell$ decay rate gets an
  extra suppression by $|V_{cb}|^2$ compared to the $k = s$ case. This brings the relevant
  new physics scale close to the electroweak scale (roughly, $(0.14)^{-1/4} m_W$), a situation
  that does not lend itself to an SMEFT analysis and requires a model dependent
  analysis instead (see, e.g. ref. [16] for relevant simplified models). Bounds from $\Upsilon$
declays [17–19] are relevant for this scenario.
• The contributions from individual scalar or tensor operators are disfavored by their different contributions to \( R(D) \) and \( R(D^*) \), by the \( B_c \) lifetime and by their modification of the differential decay rates with respect to the SM \([20–23]\). An exception to this statement is provided by a specific combination of scalar and tensor operators. We present further details on this issue in appendix A.

• Given that we focus on lepton flavor violating operators, there is no interference with the SM operators. Thus, the measurements that we discuss are sensitive only to absolute values of Wilson coefficients, and not to their phase structure.

We denote \( C_{1,3}^{\tau\ell sb} \) by \( C_{1,3}^{l} \). The \( C_{1,3}^{l} \) dependent terms can be rewritten as follows:

\[
\Lambda^2 \mathcal{L}_{NP} = \left( C_1^l + C_3^l \right) V_{is} V_{jb}^* (\overline{\tau L_i} \gamma^\mu u_{Lj})(\overline{\tau \gamma_\mu l}) + (C_1^l - C_3^l) V_{is} V_{jb}^* (\overline{\tau L_i} \gamma^\mu u_{Lj})(\overline{\tau \gamma_\mu L}) + (C_1^l - C_3^l)(\overline{\tau L_i} \gamma^\mu b_{Lj})(\overline{\tau \gamma_\mu l}) + (C_1^l + C_3^l)(\overline{\tau L_i} \gamma^\mu b_{Lj})(\overline{\tau \gamma_\mu L}) + 2 C_3^l V_{is} (\overline{\tau L_i} \gamma^\mu b_{Lj})(\overline{\tau \gamma_\mu l}) + 2 C_3^l V_{jb} (\overline{\tau L_i} \gamma^\mu s_{Lj})(\overline{\tau \gamma_\mu l}) + \text{h.c.}. \tag{2.2}
\]

Thus, the SMEFT Lagrangian terms that contribute to \( b \to c\tau\nu \) are

\[
\mathcal{L} = \left( \frac{4G_F V_{cb} \delta_{\ell\tau}}{\sqrt{2}} + \frac{2 C_3^l V_{cs}}{\Lambda^2} \right) (\overline{\tau \gamma_\mu b_{Lj}})(\overline{\tau \gamma_\mu l}). \tag{2.3}
\]

We obtain:

\[
\frac{R(D^{(*)})}{R(D^{(*)})_{\text{SM}}} = 1 + \frac{\sqrt{2}}{G_F} \text{Re} \left( V_{cs} \frac{C_3^l}{V_{cb}} \frac{C_3^l}{A^2} \right) + \sum_{\ell=e,\mu} \frac{C_3^l}{2 G_F \Lambda^4} \frac{|V_{cs}|^2}{|V_{cb}|^2}, \tag{2.4}
\]

where we assume that the contribution of the term quadratic in \( C_3^l \) is negligible compared to the term linear in \( C_3^l \).

Thus, to account for the \( R(D^{(*)}) \) puzzle by purely \( b \to c\tau\nu_\ell \), \( \ell = e, \mu \), we need

\[
\left( \frac{\sum_{\ell=e,\mu} |C_3^l|^2}{A^2} \right)^{1/2} = (0.24 \pm 0.04) \text{ TeV}^{-2} = \frac{1}{[(2.0 \pm 0.2) \text{ TeV}]^2}. \tag{2.5}
\]

On the other hand, to account for the \( R(D^{(*)}) \) puzzle by purely \( b \to c\tau\nu_\tau \), we need

\[
\frac{C_3^l}{A^2} = (0.046 \pm 0.016) \text{ TeV}^{-2} \approx \frac{1}{[(4.7 \pm 0.8) \text{ TeV}]^2}. \tag{2.6}
\]

### 3 Bounds on \( C_3^l \)

If the \( R(D^{(*)}) \) puzzle is accounted for by purely \( b \to c\tau\bar{\nu}_\ell \), eq. (2.5) implies that we need \( |C_3^l|/A^2 \sim 1/(2 \text{ TeV})^2 \). Eq. (2.2) implies that the \( C_3^l \) term contributes, via four fermi operators with the flavor structures \( s\bar{\nu}_\ell \) and \( b\bar{\nu}_\tau\nu_\ell \), to various flavor changing neutral current and lepton flavor violating processes which are forbidden in the SM. In this section, we obtain the constraints from the experimental upper bounds on such processes.
• $B_s \to \tau^\pm \mu^\mp$.
  The $B_s \to \tau^\pm \mu^\mp$ decay rate is given by
  \[
  \Gamma(B_s \to \tau^+ \mu^-) = \frac{|C_1^\mu + C_3^\mu|^2 f_{B_s}^2 m_{B_s}^2}{64 \pi} \left( 1 - \frac{m_{\tau}^2}{m_{B_s}^2} \right)^2. \tag{3.1}
  \]
  The experimental upper bound \cite{24},
  \[
  \mathcal{B}(B_s \to \tau^\pm \mu^\mp) < 4.2 \times 10^{-5}, \tag{3.2}
  \]
  implies
  \[
  \frac{|C_1^\mu + C_3^\mu|}{\Lambda^2} < 0.073 \text{ TeV}^{-2}. \tag{3.3}
  \]

• $B^+ \to K^+ \tau^+ \mu^-$.
  The $B^+ \to K^+ \tau^+ \mu^-$ branching ratio is given by
  \[
  \mathcal{B}(B^+ \to K^+ \mu^- \tau^+) = 8.2 \times 10^{-3} \text{ TeV}^4 \times \frac{|C_1^\mu + C_3^\mu|^2}{\Lambda^4}. \tag{3.4}
  \]
  The experimental upper bound \cite{25},
  \[
  \mathcal{B}(B^+ \to K^+ \mu^- \tau^+) < 2.8 \times 10^{-5}, \tag{3.5}
  \]
  implies
  \[
  \frac{|C_1^\mu + C_3^\mu|}{\Lambda^2} < 0.058 \text{ TeV}^{-2}. \tag{3.6}
  \]

• $B^+ \to K^+ \tau^+ e^-$.
  The $B^+ \to K^+ \tau^+ e^-$ branching ratio is given by
  \[
  \mathcal{B}(B^+ \to K^+ e^- \tau^+) = 8.2 \times 10^{-3} \text{ TeV}^4 \times \frac{|C_1^e + C_3^e|^2}{\Lambda^4}. \tag{3.7}
  \]
  The experimental upper bound \cite{25},
  \[
  \mathcal{B}(B^+ \to K^+ e^- \tau^+) < 1.5 \times 10^{-5}, \tag{3.8}
  \]
  implies (see also ref. [26])
  \[
  \frac{|C_1^e + C_3^e|}{\Lambda^2} < 0.044 \text{ TeV}^{-2}. \tag{3.9}
  \]

• $B^+ \to K^+ \bar{\nu}_\tau \nu_\ell$.
  The $B^+ \to K^+ \bar{\nu}_\tau \nu_\ell$ branching ratio, normalized to the SM rate, is given by
  \[
  R_{K\nu\ell} \equiv \frac{\mathcal{B}(B^+ \to K^+ \bar{\nu}_\tau \nu_\ell)}{\mathcal{B}_\text{SM}(B^+ \to K^+ \nu\bar{\nu})} = 1 + 3.5 \times 10^3 \text{ TeV}^4 \times \frac{|C_1^\ell - C_3^\ell|^2 + |C_1^\ell - C_3^\ell|^2}{\Lambda^4}. \tag{3.10}
  \]
  The experimental upper bound \cite{27, 28},
  \[
  \mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) < 1.6 \times 10^{-5}, \tag{3.11}
  \]
  which corresponds to $R_{K\nu\ell} \lesssim 4$, implies (see also ref. [29])
  \[
  \frac{|C_1^\ell - C_3^\ell|}{\Lambda^2} < 0.031 \text{ TeV}^{-2}. \tag{3.12}
  \]
From the upper bounds on $|C_{1}^{\ell} \pm C_{3}^{\ell}|$ we can obtain upper bounds on $C_{3}^{\ell}$ alone. Assuming that $C_{1}^{\ell}$ and $C_{3}^{\ell}$ are real, we obtain:

$$\frac{|C_{3}^{\ell}|}{\Lambda^{2}} < 0.044 \text{ TeV}^{-2}, \quad \frac{|C_{3}^{\mu}|}{\Lambda^{2}} < 0.037 \text{ TeV}^{-2}.$$  \hspace{1cm} (3.13)

Comparing to the requirement of eq. (2.5), we conclude that the contributions from $b \rightarrow c\tau\nu_{\ell}$ ($\ell = \mu, e$) can account for, at most, 3.4% of the deviation of the central value of $R(D^{(*)})$ from the SM value.

### 3.1 Other processes

We here list a few processes to which the operators of eq. (2.2) contribute. Due to our specific choice of flavor structure in eq. (2.1), these contributions are suppressed and provide weak limits only. With a different flavor structure, however, they might provide relevant bounds.

- **Forbidden top decays**, such as $t \rightarrow q\tau\ell$ with $q = c, u$ and $\ell = \mu, e$. There are currently no upper bounds on these decay rates [30].

- **Forbidden tau decays**, for two of which there are experimental upper bounds [31, 32]:

  $$B(\tau \rightarrow \mu\pi^{0}) < 1.1 \times 10^{-7},$$

  $$B(\tau \rightarrow e\pi^{0}) < 8.0 \times 10^{-8}.$$  \hspace{1cm} (3.14)

  Compared to the allowed $\tau \rightarrow \nu_{\tau}\bar{u}q$ ($q = d, s$), with $B(\tau \rightarrow \nu_{\tau}\bar{q}q) \sim 0.65$, there is a CKM suppression of $|V_{ub}/V_{us}|^{2} \sim 7 \times 10^{-7}$. Thus, branching ratios of $\mathcal{O}(10^{-7})$ do not provide significant bounds.

- **Allowed $\tau$ decays**: the ratio $B(\tau \rightarrow K\nu)/B(\tau \rightarrow \pi\nu)$ is modified because the contribution is only to the former. Both branching ratios are measured, with [30]

  $$R_{K/\pi} \equiv \frac{\Gamma(K^- \nu) / \Gamma(\pi^- \nu)}{6.44 \pm 0.09} \times 10^{-2}.$$  \hspace{1cm} (3.15)

  The SM gives [33]

  $$R_{K/\pi} = \frac{f_{K}^{2} |V_{us}|^{2}}{f_{\pi}^{2} |V_{ud}|^{2}} \left(1 - \frac{m_{K}^{2}}{m_{\pi}^{2}}\right)^{2} \left(1 + \delta_{LD}\right),$$  \hspace{1cm} (3.16)

  where $\delta_{LD} = (0.03 \pm 0.44)\%$ is the long distance correction, and $f_{K}/f_{\pi} = 1.189 \pm 0.007$. The new contribution to $\tau \rightarrow K\nu$ is CKM suppressed by $|V_{ub}/V_{us}|^{2} \sim 3 \times 10^{-4}$ compared to the SM contribution, and so it is well below the uncertainty from $\delta_{LD}$ and cannot be constrained.

- **Allowed $D_{s}^{+}$ decays**: the ratio $B(D_{s} \rightarrow \tau\nu)/B(D_{s} \rightarrow \mu\nu)$ is modified because the contribution is only to the former. Both branching ratios are measured, with [34]

  $$R_{\tau/\mu} = \frac{B(D_{s} \rightarrow \tau\nu)}{B(D_{s} \rightarrow \mu\nu)} = 10.73 \pm 0.88.$$  \hspace{1cm} (3.17)
The SM gives
\[ R_{\tau/\mu}^{\text{SM}} = \frac{m_\tau^2(1 - m_\tau^2/m_{D_\tau}^2)^2}{m_\mu^2(1 - m_\mu^2/m_{D_\tau}^2)^2} = 9.76. \tag{3.18} \]

Within our framework,
\[ \frac{R_{\tau/\mu}}{R_{\tau/\mu}^{\text{SM}}} = 1 + \frac{\sum_{\ell=e,\mu} |C_{3\ell}^f|^2}{8 G_F^2 \Lambda^4} \frac{|V_{cb}|^2}{|V_{cs}|^2}. \tag{3.19} \]

Given the suppression by \( (1/8)|V_{cb}/V_{cs}|^2 \sim 2 \times 10^{-4} \), we learn that \( R_{\tau/\mu} \) does not provide a significant bound.

- **Forbidden** \( D^0 \rightarrow \tau^\pm e^\mp \) **decays.** There is currently no upper bound on these rates \([30]\). The new contributions are strongly suppressed by several factors, compared to the leading semileptonic decay: CKM suppression by either \( |V_{cb}V_{us}/V_{cs}|^2 \sim 10^{-4} \) or \( |V_{ub}|^2 \sim 10^{-5} \), phase space suppression by \( (1 - m_\tau^2/m_{D_\tau}^2)^4 = 0.0084 \) and annihilation suppression by \( f_{\text{bs}}^2/m_{D_\tau}^2 \sim 0.01 \).

- **Forbidden** \( J/\psi \) **decays** \([35, 36]\):
  \[ B(J/\psi \rightarrow \mu^+\tau^-) < 2.0 \times 10^{-6}, \]
  \[ B(J/\psi \rightarrow e^+\tau^-) < 7.5 \times 10^{-8}. \tag{3.20} \]
  Compared to the allowed \( J/\psi \rightarrow \ell^+\ell^- \), with \( B(J/\psi \rightarrow \ell^+\ell^-) \sim 0.06 \), there is a CKM suppression \( |V_{cb}V_{us}|^2 \sim 1.6 \times 10^{-3} \). Furthermore \([17, 18]\),
  \[ \frac{B(J/\psi \rightarrow \tau^+\ell^-)}{B(J/\psi \rightarrow \ell^+\ell^-)} \propto \left( \frac{m_{J/\psi}}{\Lambda} \right)^4. \tag{3.21} \]
  Thus, the bound on \( \Lambda/\sqrt{|C_{3\ell}^f|} \) is of \( \mathcal{O}(6m_{J/\psi}) \) and on \( \Lambda/\sqrt{|C_{33}^u|} \) even weaker.

### 4 Collider searches

The effective operators of eq. (2.1) will contribute to the scattering process \( pp \rightarrow \tau^\pm \mu^\mp X_h \), where \( X_h \) stands for final hadrons. In this section, we estimate the upper bound on \( |C_{1^u}^u + C_{33}^u|/\Lambda^2 \) that can be obtained at the LHC at present and in the future. (For related work, see \([37–41]\) and, in particular, \([42–44]\).)

We base our estimate on the ATLAS search for new physics in \( pp \rightarrow \mu^+\mu^- \) (with up to one \( b \)-jet) at \( \sqrt{s} = 13 \text{ TeV} \) with 139 fb\(^{-1}\) of data \([45]\). (The phenomenological framework for the ATLAS analysis was suggested in ref. \([46]\).) Ref. \([45]\) obtains a bound \( \Lambda_{\mu\mu} > 2.4 \text{ TeV} \) on the scale that suppresses dimension-six \( bs\mu\mu \) contact interaction. This limit is obtained in the analysis with a \( b \)-veto \( (pp \rightarrow \mu^+\mu^- + 0b) \), by searching for events with high dimuon mass, \( m_{\mu\mu} > 1800 \text{ GeV} \). A somewhat weaker bound, \( \Lambda_{\mu\mu} > 2.0 \text{ TeV} \), is obtained in the \( b \)-tag category \( (pp \rightarrow \mu^+\mu^- + 1b) \) with \( m_{\mu\mu} > 1600 \text{ GeV} \). We deduce from these bounds the reach of ATLAS for \( \Lambda_{\tau\mu} \), the scale that suppresses dimension-six \( bs\tau\mu \) contact interaction.

The bound on \( \Lambda_{\mu\mu} \) is inferred from the upper bound on \( \sigma_{\mu\mu} \), the \( \mu\mu \) signal cross section. When comparing to it a search for \( pp \rightarrow \tau^\pm_h \mu^\mp + 0b \), one muon is replaced by a hadronically
decaying tau-lepton. Given that $B(\tau \to \text{hadrons}) \approx 2/3$, then at similar energy and for $\Lambda_{\tau\mu} = \Lambda_{\mu\mu}$, the signal cross-sections fulfill

$$\sigma_{\tau\mu}/\sigma_{\mu\mu} \approx 2/3. \quad (4.1)$$

The leading SM background at the high $m_{\mu\mu}$ is the Drell-Yan process to two muons, which is suppressed in a $\tau\mu$ final state selection. As concerns the Drell-Yan process to two tau-leptons, its contribution to the background is suppressed by demanding that one of the two tau-leptons decays hadronically (with branching ratio $\sim 2/3$) and the other muonically (with branching ratio $\sim 1/6$):

$$\sigma_{\tau\mu}/\sigma_{\mu\mu} \approx 2 \times 2/3 \times 1/6 = 2/9. \quad (4.2)$$

The next most significant SM background is the top-quark contribution, composed of $t\bar{t}$, $Wt$ and $Wt\bar{t}$. In each of these, the two final leptons arise from two independent decay chains, e.g. $t \to l^+ + \ell$ and $\bar{t} \to l^- + \ell$ in $t\bar{t}$ events. Thus,

$$\sigma_{t\mu}/\sigma_{t\mu} \approx 2 \times 2/3 = 4/3. \quad (4.3)$$

Defining $r_{Z/t} \equiv \sigma_{Z/\gamma^*}/\sigma_{t\mu}$, we have

$$\frac{\sigma_{Z/\gamma^*}}{\sigma_{t\mu}} \approx \frac{(2/9)r_{Z/t} + 4/3}{r_{Z/t} + 1}. \quad (4.4)$$

We thus estimate

$$\frac{(s/\sqrt{b})_{\tau\mu}}{(s/\sqrt{b})_{\mu\mu}} \approx \frac{2}{3} \sqrt{\frac{r_{Z/t} + 1}{(2/9)r_{Z/t} + 4/3}}. \quad (4.5)$$

For $r_{Z/t} > 1$, we have $(s/\sqrt{b})_{\tau\mu}/(s/\sqrt{b})_{\mu\mu} \gtrsim 0.75$, which is our conservative estimate. Note that if $r_{Z/t} \gtrsim 4$, the sensitivity to $\tau\mu$ is in fact stronger than to $\mu\mu$.

Given our conservative estimate, and that the signal sensitivity is fixed by experiment, the observational significance in $\tau\mu$ would be the same as in $\mu\mu$ for $s_{\tau\mu} \sim (4/3)s_{\mu\mu}$. Since $s \propto 1/\Lambda^4$, we expect that current data can put a lower bound of

$$\Lambda_{\tau\mu} > 2.2 \text{ TeV}. \quad (4.6)$$

If the HL-LHC achieves its target integrated luminosity, $L = 4000 \text{ fb}^{-1}$, and no signal is observed, the bound would be strengthened to

$$\Lambda_{\tau\mu} > 3.3 \text{ TeV}, \quad (4.7)$$

where we scaled according to $s/\sqrt{b} \propto \sqrt{L}$ since $s/\sqrt{b} \sim \sqrt{L}$. The analogous bounds $\Lambda_{ee} > 2.0(1.8) \text{ TeV}$ are also attained in ref. [45], from the analysis of $pp \to e^+e^- + 0b(1b)$ events with high dielectron mass, $m_{ee} > 1900(1500) \text{ GeV}$. We deduce from these bounds the reach of ATLAS for $\Lambda_{ee}$, the scale that suppresses dimension-six $bs\tau\tauee$ contact interaction. The analysis goes along the same lines as the $\Lambda_{\tau\mu}$ analysis above. Given the lepton flavor universality of the relevant SM interactions, there
are only negligible differences in the background cross sections. Our conservative estimates imply that current data can put a lower bound of

\[ \Lambda_{\tau e} > 1.9 \text{ TeV}. \] (4.8)

For the HL-LHC with \( L = 4000 \text{ fb}^{-1} \), and no signal observed, the bound would be strengthened to

\[ \Lambda_{\tau e} > 2.8 \text{ TeV}. \] (4.9)

For the \( \tau \ell + 0b \) (\( \ell = \mu, e \)) final states, our framework predicts additional contributions to those coming from the \( b\bar{s}\tau \ell \) contact interactions. In particular, there are also contributions from \( u\bar{c}\tau \ell \) and \( u\bar{u}\tau \ell \) contact interactions. These contributions are, however, CKM suppressed, the former by \( |V_{us}V_{cb}|^2 \sim 10^{-4} \), and the latter by \( |V_{us}V_{ub}|^2 \sim 10^{-6} \). Involving the valence \( u \)-quark, instead of the sea \( s \) or \( b \) quark, gains less than two orders of magnitude from the parton distribution function, so that these contributions can be safely neglected in our analysis.

The operators of eq. (2.2) lead also to mono-\( \tau \) signatures at the LHC. The ATLAS [47, 48] and CMS [49] experiments have searched for \( \tau \nu \) resonances, and their results have been recasted to apply to the SMEFT operators of interest to us [50–53], yielding [51]

\[ \Lambda_{\tau \nu} > 1.5 \text{ TeV}. \] (4.10)

At the HL-LHC, with integrated luminosity of \( L = 3000 \text{ fb}^{-1} \), the sensitivity would be strengthened to 2.3 TeV [52].

5 Conclusions

While the \( R(D^{(*)}) \) puzzle concerns lepton universality violation, it concerns also lepton flavor violation. Our study aimed to answer several questions in this context: can the \( R(D^{(*)}) \) puzzle be explained by purely lepton flavor violating new physics? Does the puzzle imply that the relevant new physics require non-generic flavor structure? Can searches for lepton flavor violation at the ATLAS and CMS experiments shed light on these questions?

We reached the following conclusions:

- Given that, to account for the central value of \( R(D^{(*)}) \), it is required that \( |C_{33}^\ell|/\Lambda^2 \simeq 0.24 \text{ TeV}^{-2} \), but other constraints require that \( |C_{33}^\mu|/\Lambda^2 < 0.044 \text{ TeV}^{-2} \), the contribution of \( b \to c\tau \nu_t \), with \( \ell = e, \mu \), to \( R(D^{(*)})/R(D^{(*)})_{\text{SM}} - 1 \) cannot exceed about 4% of the required shift.

- Given that, to account for the central value of \( R(D^{(*)}) \), it is required that \( |C_{33}^\ell|/\Lambda^2 \simeq 0.046 \text{ TeV}^{-2} \), but phenomenological constraints require that \( |C_{33}^\mu|/\Lambda^2 < 0.044 \text{ TeV}^{-2} \), and \( |C_{33}^\tau|/\Lambda^2 \simeq 0.037 \text{ TeV}^{-2} \), we learn that no special alignment with the \( \tau \)-direction is needed to explain the \( R(D^{(*)}) \) puzzle.

- Conversely, if operators of the form

\[ \frac{C_{33}^l}{\Lambda^2}(\bar{L}_\tau \gamma_\sigma \tau^a L_l)(\bar{Q}_s \gamma_\sigma \tau^a Q_b) \] (5.1)
have $C^\tau_3$, $C^\mu_3$ and $C^e_3$ all of the same order of magnitude, $C^\ell_3/\Lambda^2 \sim 0.04\text{TeV}^{-2}$, then the shift in $R(D^{(*)})$ will be dominated by a factor of order 30 by $C^\tau_3$, and all phenomenological constraints satisfied.

- Comparing eqs. (4.6) and (4.7) to eq. (3.6), we conclude that future searches at the (HL-)LHC will have to achieve an improvement in sensitivity by a factor $\sim (2.5)^{13}$ in order to compete with existing constraints from the $B$-factories on $|C^\mu_1 + C^\mu_3|/\Lambda^2$.

Comparing eqs. (4.8) and (4.9) to eq. (3.9), we conclude that future searches at the (HL-)LHC will have to achieve an improvement in sensitivity by a factor $\sim (8.5)^{40}$ in order to compete with existing constraints from the $B$-factories on $|C^e_1 + C^e_3|/\Lambda^2$.

### A Additional operators

In the context of $R(D^{(*)})$, the following three operators are considered, in addition to the operators of eq. (2.1):

\[
\begin{align*}
O^\ell_{SR} & = (\bar{Q}s_R)(\tau_R\ell_L), \\
O^\ell_{SL} & = (\bar{\tau_R}Q_b)(\tau_R\ell_L), \\
O^\ell_T & = (\bar{\tau_R}\sigma^{\mu\nu}Q_b)(\tau_R\sigma_{\mu\nu}\ell_L). \\
\end{align*}
\]

At low energy, we can write the effective Hamiltonian terms that are relevant to $b \rightarrow c\tau\bar{\nu}_\ell$ transitions as follows (see e.g. [54]):

\[
H_{\text{eff}} = 2\sqrt{2}G_F V_{cb}[\hat{C}^\ell_S(\bar{v}_b)(\tau_R\nu_\ell) + \hat{C}^\ell_P(\bar{\nu}_b)(\tau_R\nu_\ell) + \hat{C}^\ell_T(\bar{\tau_R}\sigma^{\mu\nu}b)(\tau_R\sigma_{\mu\nu}\nu_\ell)],
\]

where the $C^\ell_{S,P}$ coefficients are related to the $O^\ell_{SL} \pm O^\ell_{SR}$ operators. In other words, writing down the Wilson coefficients in the SMEFT as $C_X/\Lambda^2$, as in eq. (2.1), the relation with the $\hat{C}_X$ coefficients of eq. (A.2) is given by

\[
\frac{C^\ell_X}{\Lambda^2} = 1.32 \frac{\hat{C}^\ell_X}{(0.87\text{TeV})^2}.
\]

Unlike lepton flavor diagonal operators, the lepton flavor violating ones do not interfere with the SM contributions, independent of their Lorentz structure. Their contributions to various observables related to $b \rightarrow c\tau\bar{\nu}_\ell$ transitions are given by (see e.g. [54])

\[
\begin{align*}
R(D)/R(D)^{\text{SM}} & = 1 + 1.09|\hat{C}^\ell_S|^2 + 0.75|\hat{C}^\ell_P|^2, \\
R(D^{*})/R(D^{*})^{\text{SM}} & = 1 + 0.05|\hat{C}^\ell_P|^2 + 16.3|\hat{C}^\ell_T|^2, \\
BR(B_c \rightarrow \tau\nu)/BR(B_c \rightarrow \tau\nu)^{\text{SM}} & = 1 + 18.5|\hat{C}^\ell_P|^2,
\end{align*}
\]

where the Wilson coefficients $C^\ell_X$ are given at the scale $m_b$.

Accounting for the $R(D^{(*)})$ puzzle by either of these operators is disfavored compared to the one we studied above:
• While \(|\hat{C}_S^\ell|^2 \approx 0.13| can account for \(R(D)\), it leaves \(R(D^*) = R(D^*)^{\text{SM}}\).

• While \(|\hat{C}_P^\ell|^2 \approx 3| can account for \(R(D^*)\), it gives \(\text{BR}(B_c \to \tau \nu) \approx 1\).

• While \(|\hat{C}_T^\ell|^2 \approx 0.009| can account for \(R(D^*)\), it leaves \(R(D) \approx R(D)^{\text{SM}}\).

A specific combination of operators may, however, account for \(R(D)\) and \(R(D^*)\) without violating the bound from \(B_c \to \tau \nu\). The requirements are

\[
|\hat{C}_S^\ell(m_b)| \approx 0.35, \quad |\hat{C}_P^\ell(m_b)| \lesssim 1.5, \quad |\hat{C}_T^\ell(m_b)| \approx 0.09. \tag{A.5}
\]

This combination of parameters seems rather ad-hoc. A model that goes, however, in this direction is the \(R_2\) leptoquark model of refs. \([55, 56]\) (\(R_2(3, 2)^{+7/6}\) is a scalar, color-triplet, \(SU(2)\)-doublet of hypercharge \(+7/6\)). It generates at the high scale \(\Lambda\) of integrating out \(R_2\) the following Wilson coefficients:

\[
\hat{C}_S^\ell(\Lambda) = \hat{C}_P^\ell(\Lambda) = 4 \hat{C}_T^\ell(\Lambda). \tag{A.6}
\]

With \(\Lambda \approx 1\,\text{TeV}\), the RGE modifies this relation into (see e.g. \([54]\))

\[
\hat{C}_S^\ell(m_b) = \hat{C}_P^\ell(m_b) \approx 8.1 \hat{C}_T^\ell(m_b), \tag{A.7}
\]

thus predicting

\[
r_{D/D^*} \equiv \frac{[R(D)/R(D)^{\text{SM}}] - 1}{[R(D^*)/R(D^*)^{\text{SM}}] - 1} \approx 3.7. \tag{A.8}
\]

Two comments are in order:

• The original models, when fitting the data with a final \(\nu_{\tau}\), find that \(\hat{C}_S^\ell\) needs to be close to imaginary, to reduce the effect of interference terms. With a final \(\nu_{\ell}\), the interference terms vanish identically, with no need for a special phase structure.

• In the absence of interference terms, the predicted ratio \((A.8)\) is disfavored at the \(3\sigma\) level by the current experimental range (we take into account the correlation between the measurements \([1]\)):

\[
r_{D/D^*} = 0.96 \pm 0.92. \tag{A.9}
\]

Finally, let us mention that among the three operators of eq. \((A.1)\), only \(O_{SR}^\ell\) generates FCNC processes in the down sector. In particular, the contribution of \(|C_1^\mu|^2\) to the \(\Gamma(B_s \to \tau^+ \mu^-)\) decay is enhanced by \([m_{B_s}^2/(m_{\tau}(m_b + m_s))]^2\) compared to the one of \(|C_1^\mu + C_3^\mu|^2\). Thus the bound on \(|C_1^\mu|/\Lambda^2\) is a factor \(m_{B_s}/m_{\tau} \approx 3\) stronger than the bound of eq. \((3.3)\):

\[
|C_1^\mu|/\Lambda^2 < 0.024\,\text{TeV}^{-2}\] or, equivalently, \(|C_1^\mu| < 0.018\), making its contribution to \(R(D^*)\) negligible.
Acknowledgments

We thank Yoav Afik and Daniel Aloni for useful discussions. SB is supported by the grants from the Israel Science Foundation (grant number 2871/19), the German Israeli Foundation (grant number I-1506-303.7/2019) and by the Yeda-Sela (YeS) Center for Basic Research. YN is the Amos de-Shalit chair of theoretical physics, and is supported by grants from the Israel Science Foundation (grant number 1124/20), the U.S.-Israel Binational Science Foundation (BSF), Jerusalem, Israel (grant number 2018257), by the Minerva Foundation (with funding from the Federal Ministry for Education and Research), and by the Yeda-Sela (YeS) Center for Basic Research.

Open Access. This article is distributed under the terms of the Creative Commons Attribution License (CC-BY 4.0), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited. SCOAP³ supports the goals of the International Year of Basic Sciences for Sustainable Development.

References

[1] HFLAV collaboration, Averages of b-hadron, c-hadron, and τ-lepton properties as of 2018, *Eur. Phys. J. C* **81** (2021) 226 [arXiv:1909.12524] [inSPIRE].

[2] D. Bigi and P. Gambino, Revisiting $B \to D \ell \nu$, *Phys. Rev. D* **94** (2016) 094008 [arXiv:1606.08030] [inSPIRE].

[3] F.U. Bernlochner, Z. Ligeti, M. Papucci and D.J. Robinson, Combined analysis of semileptonic $B$ decays to $D$ and $D^*$: $R(D^{(*)})$, $|V_{cb}|$, and new physics, *Phys. Rev. D* **95** (2017) 115008 [Erratum ibid. **97** (2018) 059902] [arXiv:1703.05330] [inSPIRE].

[4] D. Bigi, P. Gambino and S. Schacht, $R(D^*)$, $|V_{cb}|$, and the Heavy Quark Symmetry relations between form factors, *JHEP* **11** (2017) 061 [arXiv:1707.09509] [inSPIRE].

[5] S. Jaiswal, S. Nandi and S.K. Patra, Extraction of $|V_{cb}|$ from $B \to D^{(*)}\ell\nu_{\ell}$ and the Standard Model predictions of $R(D^{(*)})$, *JHEP* **12** (2017) 060 [arXiv:1707.09977] [inSPIRE].

[6] BELLE collaboration, Measurement of $R(D)$ and $R(D^*)$ with a semileptonic tagging method, arXiv:1904.08794 [inSPIRE].

[7] LHCb collaboration, Test of Lepton Flavor Universality by the measurement of the $B^0 \to D^{*+}\tau^{+}\nu_{\tau}$ branching fraction using three-prong $\tau$ decays, *Phys. Rev. D* **97** (2018) 072013 [arXiv:1711.02505] [inSPIRE].

[8] LHCb collaboration, Measurement of the ratio of the $B^0 \to D^{*-}\tau^{+}\nu_{\tau}$ and $B^0 \to D^{*-}\mu^{+}\nu_{\mu}$ branching fractions using three-prong $\tau$-lepton decays, *Phys. Rev. Lett.* **120** (2018) 171802 [arXiv:1708.08856] [inSPIRE].

[9] BELLE collaboration, Measurement of the $\tau$ lepton polarization and $R(D^*)$ in the decay $B \to D^*\tau^{-}\bar{\nu}_{\tau}$ with one-prong hadronic $\tau$ decays at Belle, *Phys. Rev. D* **97** (2018) 012004 [arXiv:1709.00129] [inSPIRE].

[10] BELLE collaboration, Measurement of the $\tau$ lepton polarization and $R(D^*)$ in the decay $B \to D^{*}\tau^{-}\bar{\nu}_{\tau}$, *Phys. Rev. Lett.* **118** (2017) 211801 [arXiv:1612.00529] [inSPIRE].
[11] LHCb collaboration, Measurement of the ratio of branching fractions $B(B^0 \to D^{*+}\tau^-\overline{\nu}_\tau)/B(B^0 \to D^{*+}\mu^-\overline{\nu}_\mu)$, *Phys. Rev. Lett.* **115** (2015) 111803 [Erratum ibid. **115** (2015) 159901] [arXiv:1506.08614] [inSPIRE].

[12] Belle collaboration, Measurement of the branching ratio of $\bar{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$ relative to $\bar{B} \to D^{(*)}\ell^-\overline{\nu}_\ell$ decays with hadronic tagging at Belle, *Phys. Rev. D* **92** (2015) 072014 [arXiv:1507.03233] [inSPIRE].

[13] BaBar collaboration, Measurement of an Excess of $\bar{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$ Decays and Implications for Charged Higgs Bosons, *Phys. Rev. D* **88** (2013) 072012 [arXiv:1303.0571] [inSPIRE].

[14] BaBar collaboration, Evidence for an excess of $\bar{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$ decays, *Phys. Rev. Lett.* **109** (2012) 101802 [arXiv:1205.5442] [inSPIRE].

[15] F. Feruglio, P. Paradisi and A. Pattori, Revisiting Lepton Flavor Universality in B Decays, *Phys. Rev. Lett.* **118** (2017) 011801 [arXiv:1606.00524] [inSPIRE].

[16] D. Aloni, A. Efrati, Y. Grossman and Y. Nir, $\Upsilon$ and $\psi$ leptonic decays as probes of solutions to the $R_{D^*}^0$ puzzle, *JHEP* **06** (2017) 019 [arXiv:1702.07356] [inSPIRE].

[17] A. Abada, D. Bečirević, M. Lucente and O. Sumensari, Lepton flavor violating decays of vector quarkonia and of the $Z$ boson, *Phys. Rev. D* **91** (2015) 113013 [arXiv:1503.04159] [inSPIRE].

[18] D.E. Hazard and A.A. Petrov, Lepton flavor violating quarkonium decays, *Phys. Rev. D* **94** (2016) 074023 [arXiv:1607.00815] [inSPIRE].

[19] Belle collaboration, Search for charged lepton flavor violating decays of $\Upsilon(1S)$, arXiv:2201.09620 [inSPIRE].

[20] M. Blanke, Quo vadis flavour physics? *FPFCP2017* theory summary and outlook, *PoS* *FPCM2017* (2017) 042 [arXiv:1708.06326] [inSPIRE].

[21] X.-Q. Li, Y.-D. Yang and X. Zhang, Revisiting the one leptoquark solution to the $R(D^*)$ anomalies and its phenomenological implications, *JHEP* **08** (2016) 054 [arXiv:1605.09308] [inSPIRE].

[22] R. Alonso, B. Grinstein and J. Martin Camalich, Lifetime of $B^-_c$ Constrains Explanations for Anomalies in $B \to D^{(*)}\tau\nu$, *Phys. Rev. Lett.* **118** (2017) 081802 [arXiv:1611.06676] [inSPIRE].

[23] A. Celis, M. Jung, X.-Q. Li and A. Pich, Scalar contributions to $b \to c(u)\tau\nu$ transitions, *Phys. Lett. B* **771** (2017) 168 [arXiv:1612.07757] [inSPIRE].

[24] LHCb collaboration, Search for the lepton-flavour-violating decays $B_0^\pm \to \tau^\pm \mu^\mp$ and $B^0 \to \tau^\pm \mu^\mp$, *Phys. Rev. Lett.* **123** (2019) 211801 [arXiv:1905.06614] [inSPIRE].

[25] BaBar collaboration, A search for the decay modes $B^\pm \to h^\pm \tau^\pm \ell$, *Phys. Rev. D* **86** (2012) 012004 [arXiv:1204.2852] [inSPIRE].

[26] R. Bause, H. Gisbert, M. Golz and G. Hiller, Interplay of dineutrino modes with semileptonic rare $B$-decays, *JHEP* **12** (2021) 061 [arXiv:2109.01675] [inSPIRE].

[27] BaBar collaboration, Search for $B \to K^{(*)}\nu\tau$ and invisible quarkonium decays, *Phys. Rev. D* **87** (2013) 112005 [arXiv:1303.7465] [inSPIRE].

[28] Belle collaboration, Search for $B \to h\nu\nu$ decays with semileptonic tagging at Belle, *Phys. Rev. D* **96** (2017) 091101 [Addendum ibid. **97** (2018) 099902] [arXiv:1702.03224] [inSPIRE].
[29] R. Bause, H. Gisbert, M. Golz and G. Hiller, Lepton universality and lepton flavor conservation tests with dineutrino modes, Eur. Phys. J. C 82 (2022) 164 [arXiv:2007.05001] [inSPIRE].

[30] Particle Data collaboration, Review of Particle Physics, Prog. Theor. Exp. Phys. 2020 (2020) 083C01 [inSPIRE].

[31] Belle collaboration, Search for lepton flavor violating $\tau^-$ decays into $\ell^-\eta$, $\ell^-\eta'$ and $\ell^-\pi^0$, Phys. Lett. B 648 (2007) 341 [hep-ex/0703009] [inSPIRE].

[32] BABAR collaboration, Search for Lepton Flavor Violating Decays $\tau^\pm \rightarrow \ell^\pm \pi^0$, $\ell^\pm \eta$, $\ell^\pm \eta'$, Phys. Rev. Lett. 98 (2007) 061803 [hep-ex/0610067] [inSPIRE].

[33] BABAR collaboration, Measurements of Charged Current Lepton Universality and $|V_{us}|$ using Tau Lepton Decays to $e^-\bar{\nu}_e\nu_\tau$, $\mu^-\bar{\nu}_\mu\nu_\tau$, $\pi^-\nu_\tau$, and $K^-\nu_\tau$, Phys. Rev. Lett. 105 (2010) 051602 [arXiv:0912.0242] [inSPIRE].

[34] Belle collaboration, Measurements of branching fractions of leptonic and hadronic $D_{s}^+$ meson decays and extraction of the $D_{s}^+$ meson decay constant, JHEP 09 (2013) 139 [arXiv:1307.6240] [inSPIRE].

[35] BES collaboration, Search for the lepton flavor violation processes $J/\psi \rightarrow \mu \tau$ and $e\tau$, Phys. Lett. B 598 (2004) 172 [hep-ex/0406018] [inSPIRE].

[36] BESIII collaboration, Search for the charged lepton flavor violating decay $J/\psi \rightarrow e\tau$, Phys. Rev. D 103 (2021) 112007 [arXiv:2104.01705] [inSPIRE].

[37] D.A. Faroughy, A. Greljo and J.F. Kamenik, Confronting lepton flavor universality violation in $B$ decays with high-$p_T$ tau lepton searches at LHC, Phys. Lett. B 764 (2017) 126 [arXiv:1609.07138] [inSPIRE].

[38] A. Greljo, G. Isidori and D. Marzocca, On the breaking of Lepton Flavor Universality in $B$ decays, JHEP 07 (2015) 142 [arXiv:1506.01705] [inSPIRE].

[39] L. Di Luzio and M. Nardecchia, What is the scale of new physics behind the $B$-flavour anomalies?, Eur. Phys. J. C 77 (2017) 536 [arXiv:1706.01868] [inSPIRE].

[40] A.J. Buras, J. Girrbach-Noe, C. Niehoff and D.M. Straub, $B \rightarrow K^{(*)}\nu\tau$ decays in the Standard Model and beyond, JHEP 02 (2015) 184 [arXiv:1409.4557] [inSPIRE].

[41] A. Greljo and D. Marzocca, High-$p_T$ dilepton tails and flavor physics, Eur. Phys. J. C 77 (2017) 548 [arXiv:1704.09015] [inSPIRE].

[42] D. Choudhury, N. Kumar and A. Kundu, Search for an opposite sign muon-tau pair and a $b$-jet at the LHC in the context of flavor anomalies, Phys. Rev. D 100 (2019) 075001 [arXiv:1905.07982] [inSPIRE].

[43] A. Angelescu, D.A. Faroughy and O. Sumensari, Lepton Flavor Violation and Dilepton Tails at the LHC, Eur. Phys. J. C 80 (2020) 641 [arXiv:2002.06684] [inSPIRE].

[44] N. Kumar, Flavor violation at LHC in events with two opposite sign leptons and a $b$-jet, in Springer Proceedings in Physics 261, P.K. Behera, V. Bhatnagar, P. Shukla and R. Sinha eds., Springer, Berlin, Germany (2021), pp. 239–243 [arXiv:2011.12810] [inSPIRE].

[45] ATLAS collaboration, Search for New Phenomena in Final States with Two Leptons and One or No $b$-Tagged Jets at $\sqrt{s} = 13$ TeV Using the ATLAS Detector, Phys. Rev. Lett. 127 (2021) 141801 [arXiv:2105.13847] [inSPIRE].
[46] Y. Afik, J. Cohen, E. Gozani, E. Kajomovitz and Y. Rozen, Establishing a Search for $b \to s\ell^+\ell^-$ Anomalies at the LHC, JHEP 08 (2018) 056 [arXiv:1805.11402] [inSPIRE].

[47] ATLAS collaboration, Search for High-Mass Resonances Decaying to $\tau\nu$ in pp Collisions at $\sqrt{s}=13$ TeV with the ATLAS Detector, Phys. Rev. Lett. 120 (2018) 161802 [arXiv:1801.06992] [inSPIRE].

[48] ATLAS collaboration, Search for high-mass resonances in final states with a tau lepton and missing transverse momentum with the ATLAS detector, ATLAS-CONF-2021-025 (2021).

[49] CMS collaboration, Search for a $W'$ boson decaying to a $\tau$ lepton and a neutrino in proton-proton collisions at $\sqrt{s}=13$ TeV, Phys. Lett. B 792 (2019) 107 [arXiv:1807.11421] [inSPIRE].

[50] A. Greljo, J. Martin Camalich and J.D. Ruiz-Álvarez, Mono-$\tau$ Signatures at the LHC Constrain Explanations of $B$-decay Anomalies, Phys. Rev. Lett. 122 (2019) 131803 [arXiv:1811.07920] [inSPIRE].

[51] D. Marzocca, U. Min and M. Son, Bottom-Flavored Mono-Tau Tails at the LHC, JHEP 12 (2020) 035 [arXiv:2008.07541] [inSPIRE].

[52] M. Endo, S. Iguro, T. Kitahara, M. Takeuchi and R. Watanabe, Non-resonant new physics search at the LHC for the $b \to c\tau\nu$ anomalies, JHEP 02 (2022) 106 [arXiv:2111.04748] [inSPIRE].

[53] F. Jaffredo, Revisiting mono-tau tails at the LHC, Eur. Phys. J. C 82 (2022) 541 [arXiv:2112.14604] [inSPIRE].

[54] M. Blanke et al., Impact of polarization observables and $B_c \to \tau\nu$ on new physics explanations of the $b \to c\tau\nu$ anomaly, Phys. Rev. D 99 (2019) 075006 [arXiv:1811.09603] [inSPIRE].

[55] D. Bečirević, I. Doršner, S. Fajfer, N. Košnik, D.A. Faroughy and O. Sumensari, Scalar leptoquarks from grand unified theories to accommodate the $B$-physics anomalies, Phys. Rev. D 98 (2018) 055003 [arXiv:1806.05689] [inSPIRE].

[56] F. Feruglio, P. Paradisi and O. Sumensari, Implications of scalar and tensor explanations of $R_{D^{(*)}}$, JHEP 11 (2018) 191 [arXiv:1806.10155] [inSPIRE].