BSM physics and violation of lepton flavor universality

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In collaboration with

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Motivation

- A few cracks $[\approx 2 - 3\sigma]$ appeared recently in $B$-meson decays:

$$R_{D(*)} = \frac{\mathcal{B}(B \to D(*)\tau\bar{\nu})}{\mathcal{B}(B \to D(*)\ell\bar{\nu})} \ell \in (e,\mu)$$

$& \quad R_{D(*)}^{\text{exp}} > R_{D(*)}^{\text{SM}}$

$$R_{K(*)} = \left|\frac{\mathcal{B}(B \to K(*)\mu\mu)}{\mathcal{B}(B \to K(*)ee)}\right| \quad q^2 \in [q^2_{\text{min}},q^2_{\text{max}}]$$

$& \quad R_{K(*)}^{\text{exp}} < R_{K(*)}^{\text{SM}}$

$\Rightarrow$ Violation of Lepton Flavor Universality (LFU)?

This talk: (i) General considerations on BSM scenarios

(ii) A viable GUT-inspired model for $R_{D(*)}$ and $R_{K(*)}$.
\( (i) \quad R_{D(*)} = \mathcal{B}(B \to D(*)\tau\bar{\nu})/\mathcal{B}(B \to D(*)\ell\bar{\nu}) \)

**Experiment**

\[
\begin{align*}
\text{BaBar, PRL109,101802(2012)} & \quad R(D) = 0.299 \pm 0.003 \\
\text{Belle, PRD92,072014(2015)} & \quad R(D) = 0.299 \pm 0.003 \\
\text{LHCb, PRL115,111803(2015)} & \quad R(D) = 0.299 \pm 0.003 \\
\text{Belle, PRD94,072007(2016)} & \quad R(D) = 0.299 \pm 0.003 \\
\text{Belle, PRL118,211801(2017)} & \quad R(D) = 0.299 \pm 0.003 \\
\text{LHCb, PRL120,171802(2018)} & \quad R(D) = 0.299 \pm 0.003 \\
\text{Average} & \quad R(D) = 0.299 \pm 0.003 \\
\end{align*}
\]

- \( R_D \): \( B \)-factories \([\approx 2\sigma]\)
- \( R_{D^*} \): \( B \)-factories and LHCb \([< 3\sigma]\); dominated by BaBar
- LHCb confirmed tendency \( R_{J/\psi}^{\text{exp}} > R_{J/\psi}^{\text{SM}} \), i.e. \( B_c \to J/\psi\ell\bar{\nu} \)
  \( \Rightarrow \) Needs confirmation from Belle-II (and LHCb run-2)!
  \( \Rightarrow \) Other LFUV ratios will be a useful cross-check (\( R_{D_s} \), \( R_{D_s^*} \), \( R_{\Lambda_c} \) ...)

\( \chi^2 \) contours

\( \chi^2 \) probability

HFLAV Summer 2018

\( P(\chi^2) = 74\% \)
(i) \( R_{D(*)} = \mathcal{B}(B \rightarrow D(*)\tau\bar{\nu})/\mathcal{B}(B \rightarrow D(*)\ell\bar{\nu}) \)

**Theory (tree-level in SM)**

See talks by Monahan, Kronfeld and Vaquero Avilés-Casco

- \( R_D \): lattice QCD at \( q^2 \neq q_{\text{max}}^2 \) \( (w > 1) \) available for both vector and scalar form factors

\[
\langle D(k)|\bar{c}\gamma^\mu b|B(p)\rangle = \left[ (p + k)^\mu - \frac{m_B^2 - m_D^2}{q^2} q^\mu \right] f_+(q^2) + q^\mu \frac{m_B^2 - m_D^2}{q^2} f_0(q^2)
\]

with \( f_+(0) = f_0(0) \).

- \( R_{D^*} \): lattice QCD at \( q^2 \neq q_{\text{max}}^2 \) not available, scalar form factor \([A_0(q^2)]\) never computed on the lattice

*Use decay angular distributions measured at B-factories to fit the leading form factor \([A_1(q^2)]\) and extract two others as ratios wrt \( A_1(q^2) \). All other ratios from HQET (NLO in \( 1/m_{c,b} \)) [Bernlochner et al 2017] but with more generous error bars (truncation errors?)*

see also [Bigi et al. '17]
(ii) $R_{K^{(*)}} = \mathcal{B}(B \to K^{(*)}\mu\mu)/\mathcal{B}(B \to K^{(*)}ee)$

**Experiment** $\approx 4\sigma$

More intro in talk by Lisovskiyi

⇒ Needs confirmation from Belle-II!

**Theory** (loop induced in SM)

- Hadronic uncertainties cancel to a large extent
  ⇒ Clean observables!
  [Hiller et al. '03
  \textit{working below the narrow }c\bar{c}\textit{ resonances}]

- QED corrections important, $R_{K^{(*)}} = 1.00(1)$
  [Bordone et al. '16]
General considerations on BSM scenarios
Relevant questions:

- Is there a **model of New Physics** to explain these anomalies?
- Which additional **experimental signatures** should we expect?
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- Which additional **experimental signatures** should we expect?

What is the **scale of New Physics**?

- $R_{D(*)}^{\text{exp}} > R_{D(*)}^{\text{SM}} \Rightarrow \Lambda_{NP} \lesssim 3 \, \text{TeV}$ [perturbative couplings]
- $R_{K(*)}^{\text{exp}} < R_{K(*)}^{\text{SM}} \Rightarrow \Lambda_{NP} \lesssim 30 \, \text{TeV}$ see also [Di Luzio et al. 2017]
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$R_{D(*)}^{\text{exp}}$ will be the **main guideline** of my discussion

see also talks by Allanach, Bordone, Crivellin, Di Luzio, Fajfer, Faroughy, Greljo, Hiller, Isidori, Mandal, Marzocca, Nardecchia, Straub, van Dyk, ...
Effective theory for $b \rightarrow c \tau \bar{\nu}$

$$L_{\text{eff}} = -2\sqrt{2} G_F V_{cb} \left[ (1 + g_{V_L}) (\bar{c}_L \gamma_\mu b_L)(\bar{\ell}_L \gamma^\mu \nu_L) + g_{V_R} (\bar{c}_R \gamma_\mu b_R)(\bar{\ell}_L \gamma^\mu \nu_L) \\
+ g_{S_R} (\bar{c}_L b_R)(\bar{\ell}_R \nu_L) + g_{S_L} (\bar{c}_R b_L)(\bar{\ell}_R \nu_L) + g_T (\bar{c}_R \sigma_\mu \nu b_L)(\bar{\ell}_R \sigma^{\mu \nu} \nu_L) \right] + \text{h.c.}$$

NB. w/o $\nu_R$
Effective theory for $b \rightarrow c\tau \bar{\nu}$

\[ \mathcal{L}_{\text{eff}} = -2\sqrt{2} G_F V_{cb} \left[ (1 + g_{V_L}) (\bar{c}_L \gamma_\mu b_L) (\bar{\ell}_L \gamma^\mu \nu_L) + g_{V_R} (\bar{c}_R \gamma_\mu b_R) (\bar{\ell}_L \gamma^\mu \nu_L) 
\right. 
\left. + g_{S_R} (\bar{c}_L b_R) (\bar{\ell}_R \nu_L) + g_{S_L} (\bar{c}_R b_L) (\bar{\ell}_R \nu_L) + g_T (\bar{c}_R \sigma_{\mu\nu} b_L) (\bar{\ell}_R \sigma^{\mu\nu} \nu_L) \right] + \text{h.c.} \]

Few viable solutions to $R_D(*)$:

\[ \chi^2 \]

$g_{V_L} \in (0.09, 0.13)$, but not only! $g_{S_L}$ and $g_T$ are also viable

[Angelescu, Becirevic, Faroughy, OS. 1808.08179]
More exp. information is needed to distinguish among them!
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i) **Many angular observables** (e.g., $A_{fb}$, polarization asymmetries)

First measurements:

- $P_\tau(D^*)_{\text{exp}} = -0.38 \pm 0.51^{+0.21}_{-0.16}$ [Belle '17]
- $F_L(D^*)_{\text{exp}} = 0.60 \pm 0.08 \pm 0.03$ [Belle '18]

[see talk by Adamczyk]

[Becirevic et al. '16]
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ii) Other LFUV ratios:

- $R_J/\psi, R_{D_s}, R_{D_s^*}, R_{\Lambda_c} \ldots$ see talks by Morris and Rotondo
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ii) Other LFUV ratios:

- $R_{J/\psi}$, $R_{Ds}$, $R_{Ds^*}$, $R_{\Lambda_c}$… see talks by Morris and Rotondo

iii) Leptonic observables (via RGE effects)

- $g_{VL} \Rightarrow$ Corrections to $Z \to \ell\ell$, $\tau \to \mu\nu\bar{\nu}$ [Feruglio et al. 2015]
- $g_{SL}$ and $g_{T} \Rightarrow$ Enhanced contributions to $H \to \tau\tau$ and $(g - 2)_\tau$
  [Feruglio, Paradisi, OS. 1806.10155]
$R_{D(*)}^{\text{exp}} > R_{D(*)}^{\text{SM}}$ require new bosons at the TeV scale:

- Loop constraints: e.g. $\tau \rightarrow \mu \nu \bar{\nu}$, $Z \rightarrow \ell \ell$ [Feruglio et al., '16]
- LHC direct and indirect bounds [Greljo et al. '15, Faroughy et al., '16]

In Summary:

- Charge Higgs solutions are in tension with $\tau_{B_c}$ constraint [Alonso et al. '16]
- Minimal $W'$ models: tension with high-$p_T$ ditau constraints
  $\Rightarrow$ Still viable in models with $\nu_R$ [Greljo et al. '18, Asadi et al. '18]
- Scalar and vector leptoquarks (LQ) are the best candidates so far.
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Challenges for New Physics:

- Loop constraints: e.g. $\tau \rightarrow \mu \nu \bar{\nu}$, $Z \rightarrow \ell\ell$ [Feruglio et al., '16]
- LHC direct and indirect bounds [Greljo et al. '15, Faroughy et al., '16]
$\frac{R_{D(*)}^{\text{exp}}}{R_{D(*)}^{\text{SM}}} > 1$ require new bosons at the TeV scale:

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Leptoquarks for $R_D(\ast)$

<table>
<thead>
<tr>
<th>Model</th>
<th>$g_{\text{eff}}^{b\rightarrow c\tau\bar{\nu}} (\mu = m_\Delta)$</th>
<th>$R_D(\ast)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1 = (\bar{3}, 1, 1/3)$</td>
<td>$g_{V_L}, g_{S_L} = -4 g_T$</td>
<td>✓</td>
</tr>
<tr>
<td>$R_2 = (3, 2, 7/6)$</td>
<td>$g_{S_L} = 4 g_T$</td>
<td>✓</td>
</tr>
<tr>
<td>$S_3 = (\bar{3}, 3, 1/3)$</td>
<td>$g_{V_L}$</td>
<td>×</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>$U_1 = (3, 1, 2/3)$</td>
<td>$g_{V_L}, g_{S_R}$</td>
<td>✓</td>
</tr>
<tr>
<td>$U_3 = (3, 3, 2/3)$</td>
<td>$g_{V_L}$</td>
<td>×</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Viable models for $R_D(\ast)$: [Angelescu, Becirevic, Faroughy, OS. 1808.08179]

- $U_1 (g_{V_L}), S_1 (g_{V_L} \text{ and } g_{S_L} = -4 g_T), \text{ and } R_2 (g_{S_L} = 4 g_T \in \mathbb{C})$
- Some models are excluded by other flavor constraints: $B \rightarrow K \nu\bar{\nu}, \Delta m_{B_s} \ldots$
- Possibility to distinguish them by using other $b \rightarrow c\ell\nu$ observables!

cf. e.g. [Becirevic et al. '16, Alonso et al. '16]
### Leptoquarks for $R_D(\ast)$ and $R_K(\ast)$

[Angelescu, Becirevic, Faroughy, OS. 1808.08179]

see also [Greljo et al. '17]

<table>
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</tr>
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<tbody>
<tr>
<td>$S_1 = (\bar{3}, 1, 1/3)$</td>
<td>✓</td>
<td>✓*</td>
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</tr>
<tr>
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<td>✓*</td>
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</tr>
<tr>
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<td>✓*</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

- Building a model that can **solve all anomalies** is a very challenging task!
- Only $U_1$ can do it, but **UV completion needed** (more parameters).
  \[\Rightarrow\] Possible in Pati-Salam models: [Di Luzio et al. '17, Bordone et al. '17…]
- Two scalar LQs can also do the job (no extra parameters):
  \[\Rightarrow\] $S_1$ and $S_3$ [Crivellin et al. '17, Marzocca. '18], $R_2$ and $S_3$ [Becirevic et al. '18].
A viable GUT-inspired model for $R_D(*)$ and $R_K(*)$

[Becirevic, Dorsner, Fajfer, Faroughy, Kosnik, OS. 1806.05689]
Two scalar leptoquarks

• Prefer scalar to vector LQ to remain minimalistic in terms of new parameters and to be able to compute loops (VLQ – need UV completion)

• One scalar LQ alone cannot accommodate all $B$-physics anomalies without getting into trouble with other flavor observables.

[Angelescu, Becirevic, Faroughy and OS. 1808.08179]
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- In flavor basis

$$\mathcal{L} \supset y_R^{ij} \bar{Q}_i \ell_R^j R_2 + y_L^{ij} \bar{u}_{Ri} L_j \tilde{R}_2^+ + y^{ij} \bar{Q}_i^C i \tau_2 (\tau_k S_3^k) L_j + \text{h.c.}$$

$$R_2 = (3, 2, 7/6), \quad S_3 = (\bar{3}, 3, 1/3)$$

- In mass-eigenstates basis

$$\mathcal{L} \supset (V_{CKM} y_R E_R^\dagger)^{ij} \bar{u}_{Li}^l \ell_{Rj}^l R_2^{(5/3)} + (y_R E_R^\dagger)^{ij} \bar{d}_{Li}^l \ell_{Rj}^l R_2^{(2/3)}$$

$$+ (U_R y_L U_{PMNS})^{ij} \bar{u}_{Ri}^l \nu_{Lj}^l R_2^{(2/3)} - (U_R y_L)^{ij} \bar{u}_{Ri}^l \ell_{Lj}^l R_2^{(5/3)}$$

$$- (y U_{PMNS})^{ij} \bar{d}_{Li}^l \nu_{Lj}^l S_3^{(1/3)} - \sqrt{2} y^{ij} \bar{d}_{Li}^l \ell_{Lj}^l S_3^{(4/3)}$$

$$+ \sqrt{2} (V_{CKM}^* y U_{PMNS})^{ij} \bar{u}_{Li}^l \nu_{Lj}^l S_3^{(-2/3)} - (V_{CKM}^* y)^{ij} \bar{u}_{Li}^l \ell_{Lj}^l S_3^{(1/3)} + \text{h.c.}$$
\( R_2 = (3, 2, 7/6), \quad S_3 = (\bar{3}, 3, 1/3) \)

\[
\mathcal{L} \supset \left( V_{\text{CKM}} y_R E_R^\dagger \right)^{ij} \bar{u}_{Li}^\prime \ell_{Rj}^\prime R_2^{(5/3)} + \left( y_R E_R^\dagger \right)^{ij} \bar{d}_{Li}^\prime \ell_{Rj}^\prime R_2^{(2/3)}
\]
\[
+ (U_R y_L U_{\text{PMNS}})^{ij} \bar{u}_{Ri}^\prime \nu_{Lj}^\prime R_2^{(2/3)} - (U_R y_L)^{ij} \bar{u}_{Ri}^\prime \ell_{Lj} R_2^{(5/3)}
\]
\[
- (y U_{\text{PMNS}})^{ij} \bar{d}_{Li}^C \nu_{Lj}^\prime S_3^{(1/3)} - \sqrt{2} y^{ij} \bar{d}_{Li}^C \ell_{Lj} S_3^{(4/3)}
\]
\[
+ \sqrt{2} (V_{\text{CKM}}^* y U_{\text{PMNS}})^{ij} \bar{u}_{Li}^C \nu_{Lj} S_3^{(-2/3)} - (V_{\text{CKM}}^* y)^{ij} \bar{u}_{Li}^C \ell_{Lj} S_3^{(1/3)} + \text{h.c.}
\]

and assume

\[
y_R = y_R^T \quad y = -y_L
\]

\[
y_R E_R^\dagger = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_{R}^{b\tau} \end{pmatrix}, \quad U_R y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{L}^{c\mu} & y_{L}^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}, \quad U_R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{pmatrix}
\]

Parameters: \( m_{R_2}, m_{S_3}, y_{R}^{b\tau}, y_{L}^{c\mu}, y_{L}^{c\tau} \) and \( \theta \)
Effective Lagrangian at \( \mu \approx m_{LQ} \):

- \( b \rightarrow c\tau\bar{\nu} \):
  \[ \propto \frac{y_L^{c\tau} y_R^{b\tau}}{m_{R_2}^2} \left[ (\bar{c}_R b_L)(\bar{\tau}_R \nu_L) + \frac{1}{4} (\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu} \nu_L) \right] + \ldots \]

- \( b \rightarrow s\mu\mu \):
  \[ \propto \sin 2\theta \frac{|y_L^{c\mu}|^2}{m_{S_3}^2} (\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_{\mu\mu} \mu_L) \]

- \( \Delta m_{B_s} \):
  \[ \propto \sin^2 2\theta \frac{\left[ (y_L^{c\mu})^2 + (y_L^{c\tau})^2 \right]^2}{m_{S_3}^2} (\bar{s}_L \gamma^\mu b_L)^2 \]

⇒ Suppression mechanism of \( b \rightarrow s\mu\mu \) wrt \( b \rightarrow c\tau\bar{\nu} \) for small \( \sin 2\theta \).

⇒ Phenomenology suggests \( \theta \approx \pi/2 \) and \( y_R^{b\tau} \) complex
Other notable constraints...

- $R_K^{\text{exp}} = 2.488(10) \times 10^{-5}$ [PDG], $R_K^{\text{SM}} = 2.477(1) \times 10^{-5}$ [Cirigliano 2007]
  
  $$R_K^{\text{exp}} = \frac{\Gamma(K^- \rightarrow e^- \bar{\nu})}{\Gamma(K^- \rightarrow \mu^- \bar{\nu})}$$

- $R_D^{\text{exp}} = 0.995(45)$ [Belle 2017], $R_D^{\ast \text{exp}} = 1.04(5)$ [Belle 2016]
  
  $$R_D^{\ast \text{exp}} = \frac{\Gamma(B \rightarrow D^{(*)} \mu \bar{\nu})}{\Gamma(B \rightarrow D^{(*)} e \bar{\nu})}$$

- $\mathcal{B}(\tau \rightarrow \mu \phi) < 8.4 \times 10^{-8}$ [PDG]

- Loops: $\Delta m_{B_s}^{\text{exp}} = 17.7(2) \text{ ps}^{-1}$ [PDG], $\Delta m_{B_s}^{\text{SM}} = (19.0 \pm 2.4) \text{ ps}^{-1}$ [FLAG 2016]

- Loops: $Z \rightarrow \mu \mu, Z \rightarrow \tau \tau, Z \rightarrow \nu \nu$ [PDG]

  $$\frac{g_\tau^V}{g_e^V} = 0.959(29), \quad \frac{g_\tau^A}{g_e^A} = 1.0019(15), \quad \frac{g_\mu^V}{g_e^V} = 0.961(61), \quad \frac{g_\mu^A}{g_e^A} = 1.0001(13)$$

  $$N_\nu^{\text{exp}} = 2.9840(82)$$
Results and predictions:

For $\Re[g_{SL}] = 0$ we get $\Im[g_{SL}] = 0.59^{+0.13(+0.20)}_{-0.14(-0.29)}$

$\Re[g_{SL}] = 0.8$ TeV, $m_{S_3} = 2.0$ TeV, $|\theta| \approx \pi/2$

$g_{SL} = 4 g_T$

NB.
Direct searches (projections to 100 fb$^{-1}$)

$m_{R_2} = 0.8$ TeV, $m_{S_3} = 2.0$ TeV, $|\theta| \approx \pi/2$
Several **distinctive predictions** wrt the SM:

- **Enhancement** of $\mathcal{B}(B \to K \nu \bar{\nu})$ by $\gtrsim 50\%$ wrt to the SM [Belle-II]

- **Upper and lower bounds** on the LFV rates: $\mathcal{B}(B \to K \mu \tau) \gtrsim 2 \times 10^{-7}$

  NB. $\mathcal{B}(B \to K^* \mu \tau)/\mathcal{B}(B \to K \mu \tau) \approx 1.8$, $\mathcal{B}(B \to K \mu \tau)/\mathcal{B}(B_s \to \mu \tau) \approx 1.25$ [Becirevic, OS, Zukanovich. 1602.00881]
Intermezzo

- $\mathcal{B}(B \rightarrow K^{(*)}\mu\tau)$ can confirm/refute other solutions of the $B$-anomalies too!
- For the $U_1$ model: $pp \rightarrow \ell\ell$ constraints set a model independent lower bound $\mathcal{B}(B \rightarrow K\mu\tau) \gtrsim \text{few} \times 10^{-7}$ (to be improved with more data!)

Even larger predictions found in a UV-complete model! [Bordone et al. '18].

- BaBar: $\mathcal{B}(B \rightarrow K\mu\tau) < 4.8 \times 10^{-5}$ (90\%CL). Can LHCb do better?
Simple and viable $SU(5)$ GUT

- Choice of Yukawas was biased by $SU(5)$ GUT aspirations

- Scalars: $R_2 \in 45, 50$, $S_3 \in 45$. SM matter fields in $5_i$ and $10_i$

- Operators $10_i 10_j 45$ forbidden to prevent proton decay [Dorsner et al 2017]

- Available operators

\[
10_i 5_j 45 : \quad y_2^{RL} \overline{u}_i^R R_2^a \varepsilon^{ab} L_j^b, \quad y_3^{LL} \overline{Q}_i^j \varepsilon^{ab} (\tau^k S_3^k)^{bc} L_L^c.
\]

\[
10_i 10_j 50 : \quad y_2^{LR} \overline{e}_i^R R_2^a Q_L^i,^a.
\]

- While breaking $SU(5)$ down to SM the two $R_2$'s mix – one can be light and the other (very) heavy. Thus our initial Lagrangian!

- The **Yukawas** determined from flavor physics observables at low energy remain perturbative ($\lesssim \sqrt{4\pi}$) up to the GUT scale, using one-loop running [Wise et al 2014, c.f. back-up]
Summary and perspectives

○ Building a viable model which accommodates the $B$-physics anomalies and remains consistent with all other measured flavor observables is difficult. **Data-driven model building!**

○ We propose a minimalistic model with two light scalar leptoquarks. Model passes all constraints and satisfactorily accommodates $B$-physics anomalies. **Model is of $V-A$ structure for \( b \rightarrow s \ell\ell \), but NOT for \( b \rightarrow c \ell\bar{\nu} \)**

○ Our model is GUT inspired and allows for unification with only two light LQs. **Yukawas remain perturbative after 1-loop running to \( \Lambda_{\text{GUT}} \)**

○ Our model offers several predictions to be tested at Belle-II and LHC(b). **e.g.,** \( 2 \times 10^{-7} \lesssim \mathcal{B}(B \rightarrow K \mu\tau) \lesssim 8 \times 10^{-7} \)**

○ Results of the direct LHC searches might soon become relevant too. **Opportunities for direct searches at LHC!**
Thank you!

This project has received support from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 674896.
Back-up
- **3.9σ combined** deviation from the SM [theory error under control?]
- Discrepancy driven by oldest exp. results (BaBar and LHCb).
- Needs **confirmation** from Belle-II (and LHCb run-2)!
### SM predictions for $R_{D(*)}$

<table>
<thead>
<tr>
<th>Ref.</th>
<th>$R_D$</th>
<th>$R_{D*}$</th>
<th>dev. ($R_D$)</th>
<th>dev. ($R_{D*}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. [HFLAV]</td>
<td>$0.41(5)$</td>
<td>$0.304(15)$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>LQCD [FLAG]</td>
<td>$0.300(8)$</td>
<td>–</td>
<td>$2.3\sigma$</td>
<td>–</td>
</tr>
<tr>
<td>Fajfer et al. ’12</td>
<td>$0.296(16)$</td>
<td>$0.252(3)$</td>
<td>$2.3\sigma$</td>
<td>$3.4\sigma$</td>
</tr>
<tr>
<td>Bigi et al. ’16</td>
<td>$0.299(3)$</td>
<td>–</td>
<td>$2.3\sigma$</td>
<td>–</td>
</tr>
<tr>
<td>Bigi et al. ’17</td>
<td>–</td>
<td>$0.260(8)$</td>
<td>–</td>
<td>$2.6\sigma$</td>
</tr>
<tr>
<td>Bernlochner et al. ’17</td>
<td>$0.298(3)$</td>
<td>$0.257(3)$</td>
<td>$2.4\sigma$</td>
<td>$3.1\sigma$</td>
</tr>
</tbody>
</table>

- LQCD determination of $A_0(q^2)$ would be very helpful.
- Soft photon corrections: first steps in [de Boer et al. ’18] Disentangling structure dependent terms, important!? – More work needed.
\[
\frac{R_{D(*)}}{R_{D(*)}^{SM}} = 1 + a_S^{D(*)} |g_S^\tau|^2 + a_P^{D(*)} |g_P^\tau|^2 + a_T^{D(*)} |g_T^\tau|^2 \\
+ a_{SV_L}^{D(*)} \text{Re}[g_S^\tau] + a_{PV_L}^{D(*)} \text{Re}[g_P^\tau] + a_{TV_L}^{D(*)} \text{Re}[g_T^\tau],
\]

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>(a_S^M)</th>
<th>(a_{SV_L}^M)</th>
<th>(a_P^M)</th>
<th>(a_{PV_L}^M)</th>
<th>(a_T^M)</th>
<th>(a_{TV_L}^M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B \to D)</td>
<td>1.08(1)</td>
<td>1.54(2)</td>
<td>0</td>
<td>0</td>
<td>0.83(5)</td>
<td>1.09(3)</td>
</tr>
<tr>
<td>(B \to D^*)</td>
<td>0</td>
<td>0</td>
<td>0.0473(5)</td>
<td>0.14(2)</td>
<td>17.3(16)</td>
<td>-5.1(4)</td>
</tr>
</tbody>
</table>
Results – a few predictions

✓ OK with $B(B_c \to \tau \nu) < 30\%$ [Alonso et al. ’17], and $\lesssim 10\%$ [Akeroyd et al. ’17]

✓ $R_{J/\psi} > R_{J/\psi}^{SM}$ increases $\leftarrow$ new FF estimate QCDSR + latt

[Becirevic, Leljak,Melic, OS. ’18]
\[ 16\pi^2 \frac{d \log y_{R}^{b\tau}}{d \log \mu} = |y_{L}^{c\mu}|^2 + |y_{L}^{c\tau}|^2 + \frac{9}{2} |y_{R}^{b\tau}|^2 + \frac{y_{i}^2}{2} + \ldots \]

\( m_{S_3} = 2 \text{ TeV}, m_{R_2} = 0.8 \text{ TeV} \)