# $B$-physics and lepton flavor (universality) violation

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hep-ph/1806.10155, 1806.05689

In collaboration with

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# Motivation

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

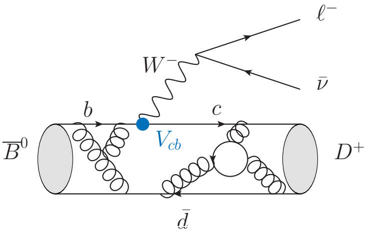
$$R_{D^{(*)}} = \frac{\mathcal{B}(B\to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B\to D^{(*)}\ell\bar{\nu})}_{\ell\in(e,\mu)} \qquad \& \qquad R_{D^{(*)}}^{\mathrm{exp}} > R_{D^{(*)}}^{\mathrm{SM}}$$

$$R_{K^{(*)}} = \frac{\mathcal{B}(B\to K^{(*)}\mu\mu)}{\mathcal{B}(B\to K^{(*)}ee)}\bigg|_{q^2\in[q^2_{\mathrm{min}},q^2_{\mathrm{max}}]} \qquad \& \qquad R_{K^{(*)}}^{\mathrm{exp}} < R_{K^{(*)}}^{\mathrm{SM}}$$

$\Rightarrow$ Violation of **L**epton **F**lavor **U**niversality (LFU)?

This talk: (i) EFT implications and (ii) a viable model for $R_{K^{(*)}}$ and $R_{D^{(*)}}$.

# EFT implications of $R_{D^{(*)}}$




[Feruglio, Paradisi, OS. 1806.10155]

## (i) $R_{D^{(*)}} = \mathcal{B}(B \to D^{(*)}\tau\bar{\nu})/\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})$

Experiment

*More intro in talk by Crivellin*

- $R_D$: $B$-factories $[\approx 2\sigma]$
- $R_{D^*}$: $B$-factories and LHCb $[\approx 3\sigma]$
- LHCb confirmed tendency $R_{J/\psi}^{\rm exp} > R_{J/\psi}^{\rm SM}$, i.e. $B_c \to J/\psi\ell\bar{\nu}$

  $\Rightarrow$ Needs confirmation from Belle-II (and LHCb run-2)!

Theory (tree-level in SM)

- $R_D$: form factors computed on the lattice [MILC 2015, HPQCD 2015]
- $R_{D^*}$: leading form factor from experiment (with $l = e, \mu$), subleading form factor from HQET with generous error bars

See back-up for more details

# Effective theory for $b \to c\tau\bar{\nu}$

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

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**General messages:**

- $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariance [Aebischer et al. 2016]
  $\Rightarrow g_{V_R}$ LFU at dimension-6 ($W\bar{c}_R b_R$ vertex)

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- Few viable solutions to $R_{D^{(*)}}$:
  - e.g. $g_{V_L} \in (0.09, 0.13)$, but not only! $g_{S_L}$ and $g_T$ are also viable
    cf. e.g. [Angelescu, Becirevic, Faroughy, OS. 1808.08179]

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- Perturbativity $\Rightarrow \Lambda_{\rm NP} \lesssim 3$ TeV see also [Di Luzio et al. 2017]
  $\Rightarrow$ Electroweak quantum effects can be large!

# Electroweak loops

see also [Jenkins et al, Alonso et al. 2013]

- Useful in the "$V-A$" scenario (i.e. $g_{V_L}$): [Feruglio et al. 2017]

  $\Rightarrow$ Crucial constraints from $\mathcal{B}(Z \to \tau\tau)$ and $\mathcal{B}(\tau \to \mu\nu\bar{\nu})$

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Which observables receive contributions from the RGE evolution of scalar and tensor operators?

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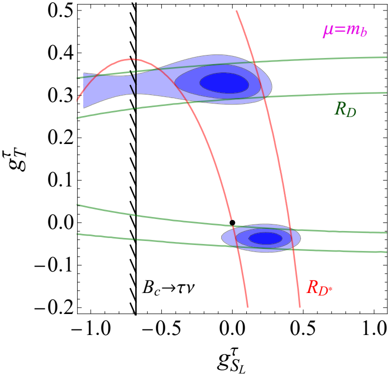
Which observables receive contributions from the RGE evolution of scalar and tensor operators?

$$\mathcal{O}_{S_L} = (\bar{c}_R b_L)(\bar{\ell}_R \nu_L)$$

$$\mathcal{O}_T = (\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\ell}_R \sigma^{\mu\nu} \nu_L)$$

[Feruglio, Paradisi, OS. 1806.10155]



## Our setup:

[Feruglio, Paradisi, OS. 1806.10155]

$$\mathcal{L}_{\rm NP} \supset \frac{C_{S_L}}{\Lambda^2}\,(\overline{L}\ell_R)i\sigma_2(\overline{Q}u_R) + \frac{C_T}{\Lambda^2}\,(\overline{L}\sigma_{\mu\nu}\ell_R)i\sigma_2(\overline{Q}\sigma^{\mu\nu}u_R) + \text{h.c.}$$

*[flavor indices omitted]*

**Matching**: $g_{S_L} \Leftrightarrow C_{S_L}$, $g_T \Leftrightarrow C_T$ ; + neutral components

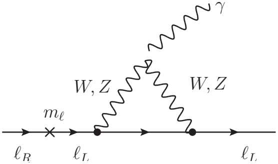
**(Minimal) flavor assumptions**: cf. back-up

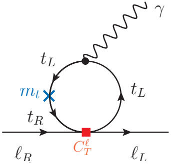
- Coupling to 3rd fermion generation (flavor basis).
- Negligible RH lepton mixing.
- Nonzero angle $\theta_U \equiv \theta_{23}$ for RH quarks.

Which operators are generated by RGE effects?

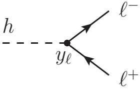
- Large enhancement ($\propto m_t/m_\tau$) of $(g-2)_\tau$ and $\mathcal{B}(H \to \tau\tau)$:

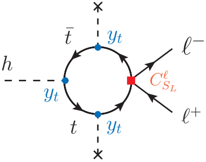
(i) $\delta\mathcal{L}_{\text{dip}} \propto C_T^\ell \, m_t \, \dfrac{\log(\Lambda/m_t)}{16\pi^2\Lambda^2} \, \overline{\ell_L}\sigma_{\mu\nu}\ell_R F^{\mu\nu} + \dots$

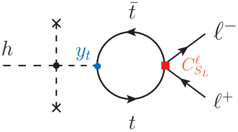





(ii) $\delta\mathcal{L}_H \propto C_{S_L}^\ell \, y_t(y_t^2 - \lambda) \, \dfrac{\log(\Lambda/m_t)}{16\pi^2\Lambda^2} \, (H^\dagger H)(\overline{L}\ell_R H) + \text{h.c.}$





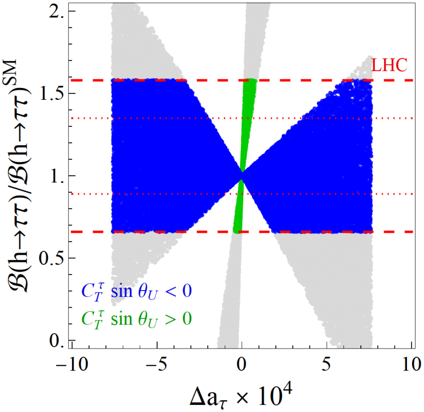



- On the other hand, no sizable modification of $W, Z$ decays.

## Predictions

[Feruglio, Paradisi, OS. 1806.10155]

- Two distinct solutions to $R_{D^{(*)}}$ (blue and green)
- LHC results on $\mathcal{B}(h \to \tau\tau)$ are already useful!
- $|\Delta a_\tau|$ as large as $8 \times 10^{-4}$ !
    - LEP and SLD: $-0.007 < a_\tau^{\rm exp} < 0.004$
    - Can we do better?



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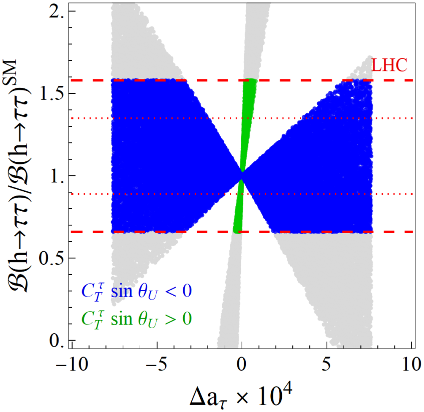



⇒ Loop effects can be large!

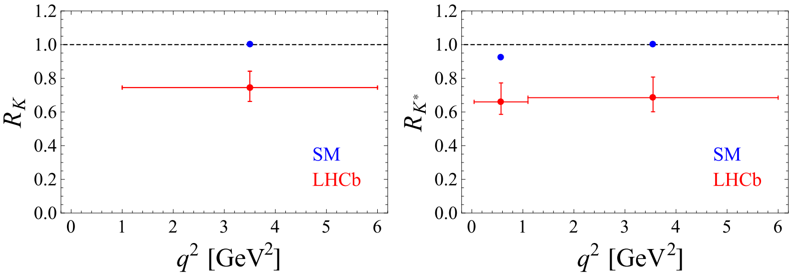
⇒ Alternative test of semileptonic operators with leptonic observables.

# A viable model for $R_{D^{(*)}}$ and $R_{K^{(*)}}$

[Becirevic, Dorsner, Fajfer, Faroughy, Kosnik, OS. 1806.05689]

## (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 Crivellin*




$\Rightarrow$ Needs confirmation from Belle-II!

Theory (loop induced in SM)

- Hadronic uncertainties cancel to a large extent
  $\Rightarrow$ Clean observables! [*working below the narrow $c\bar{c}$ resonances*]
- QED corrections important, $R_{K^{(*)}} = 1.00(1)$, [Bordone et al. 2016]

## Two scalar leptoquarks

Becirevic, Dorsner, Fajfer, Faroughy, Kosnik, OS. 1806.05689

- Leptoquarks (LQ) are the best candidates to explain the $B$-anomalies.

  [Buttazzo et al. 2017]

- 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.

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- In flavor basis

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

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

  and assume

$$y_R = y_R^T \qquad y = -y_L$$

- Parameters: $m_{R_2}$, $m_{S_3}$, $y_R^{b\tau}$, $y_L^{c\mu}$, $y_L^{c\tau}$ and $\theta$

Effective Lagrangian at $\mu \approx m_{\rm LQ}$:

- $b \to c\tau\bar{\nu}$  $[\Lambda_{\rm NP}/g \approx 1~\text{TeV}]$

$$\propto \frac{y_L^{c\tau}\, y_R^{b\tau\,*}}{m_{R_2}^2}\left[(\bar{c}_R b_L)(\bar{\tau}_R \nu_L) + \frac{1}{4}(\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu} \nu_L)\right] + \dots$$

- $b \to s\mu\mu$  $[\Lambda_{\rm NP}/g \approx 30~\text{TeV}]$:

$$\propto \sin 2\theta \, \frac{|y_L^{c\mu}|^2}{m_{S_3}^2}\,(\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L)$$

$\Rightarrow$ Suppression mechanism of $b \to s\mu\mu$ wrt $b \to c\tau\bar{\nu}$ for small $\sin 2\theta$

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$\Rightarrow$ Suppression mechanism of $b \to s\mu\mu$ wrt $b \to c\tau\bar{\nu}$ for small $\sin 2\theta$

Phenomenology suggests $\theta \approx \pi/2$ and $y_R^{b\tau}$ complex

# Other notable constraints...

- $R_{e/\mu}^{K\ \mathrm{exp}} = 2.488(10)\times 10^{-5}$ [PDG], $R_{e/\mu}^{K\ \mathrm{SM}} = 2.477(1)\times 10^{-5}$ [Cirigliano 2007]

$$R_{e/\mu}^{K} = \frac{\Gamma(K^- \to e^-\bar{\nu})}{\Gamma(K^- \to \mu^-\bar{\nu})}$$

- $R_{\mu/e}^{D\ \mathrm{exp}} = 0.995(45)$ [Belle 2017], $R_{\mu/e}^{D^*\ \mathrm{exp}} = 1.04(5)$ [Belle 2016]

$$R_{\mu/e}^{D^{(*)}} = \frac{\Gamma(B \to D^{(*)}\mu\bar{\nu})}{\Gamma(B \to D^{(*)}e\bar{\nu})}$$

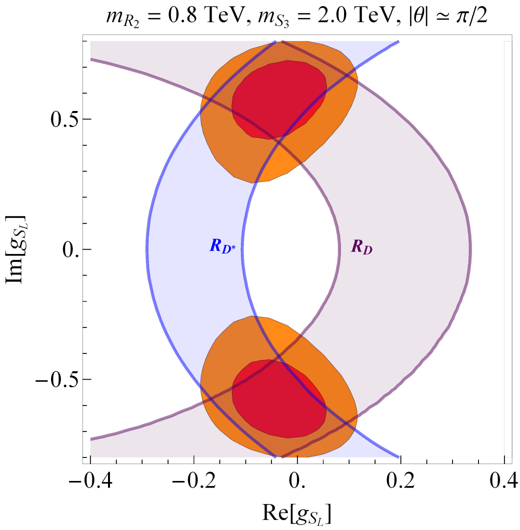
- $\mathcal{B}(\tau \to \mu\phi) < 8.4\times 10^{-8}$ [PDG]
- Loops: $\Delta m_{B_s}^{\mathrm{exp}} = 17.7(2)\ \mathrm{ps}^{-1}$ [PDG], $\Delta m_{B_s}^{\mathrm{SM}} = (19.0\pm 2.4)\ \mathrm{ps}^{-1}$ [FLAG 2016]
- Loops: $Z\to\mu\mu$, $Z\to\tau\tau$, $Z\to\nu\nu$ [PDG]

$$\frac{g_V^\tau}{g_V^e} = 0.959(29)\,, \quad \frac{g_A^\tau}{g_A^e} = 1.0019(15) \qquad \frac{g_V^\mu}{g_V^e} = 0.961(61)\,, \quad \frac{g_A^\mu}{g_A^e} = 1.0001(13)$$

$$N_\nu^{\mathrm{exp}} = 2.9840(82)$$

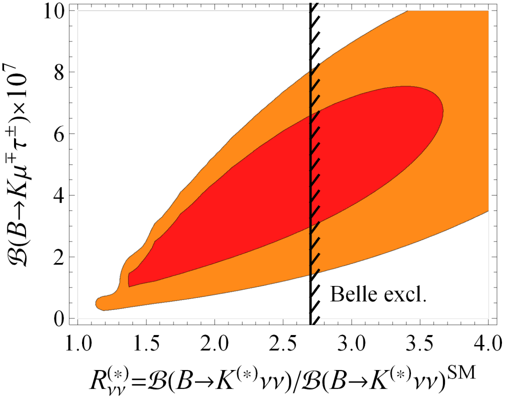
# Results and predictions:

**NB.** $g_{S_L} = 4\, g_T$




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

Several **distinctive predictions** wrt the SM:

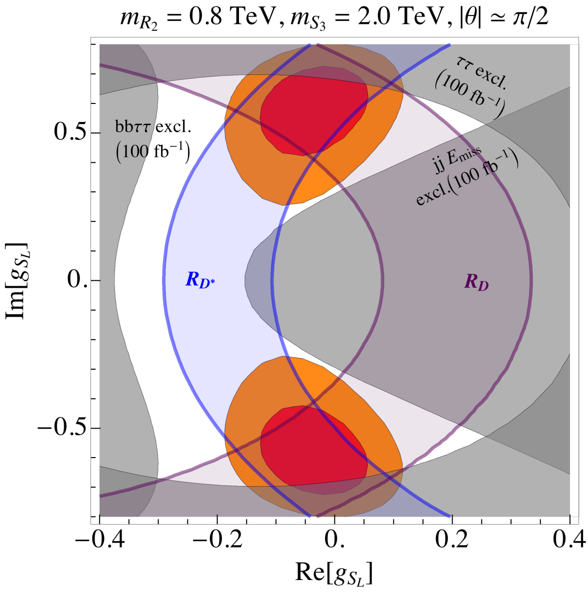



- **Enhancement** of $\mathcal{B}(B\to K\nu\bar{\nu})$ by $\gtrsim 50\%$ wrt to the SM [Belle-II]
- Upper and **lower bounds** on the **LFV** rates: $\mathcal{B}(B\to K\mu\tau)\gtrsim 2\times 10^{-7}$

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. 2015]

# Direct searches (projections to $100\ \text{fb}^{-1}$)



# Simple and viable $SU(5)$ GUT

- Choice of Yukawas was biased by $SU(5)$ GUT aspirations
- Scalars: $R_2 \in \underline{\mathbf{45}}, \underline{\mathbf{50}}$, $S_3 \in \underline{\mathbf{45}}$. SM matter fields in $\mathbf{5}_i$ and $\mathbf{10}_i$
- Operators $\mathbf{10}_i \mathbf{10}_j \underline{\mathbf{45}}$ forbidden to prevent proton decay [Dorsner et al 2017]
- Available operators

$$\mathbf{10}_i \mathbf{5}_j \underline{\mathbf{45}}: \quad y_{2\,ij}^{RL}\, \overline{u}_R^i R_2^a \varepsilon^{ab} L_L^{j,b}, \quad y_{3ij}^{LL}\, \overline{Q^C}_L^{i,a} \varepsilon^{ab} (\tau^k S_3^k)^{bc} L_L^{j,c}$$

$$\mathbf{10}_i \mathbf{10}_j \underline{\mathbf{50}}: \quad y_{2\,ij}^{LR}\, \overline{e}_R^i R_2^{a\,*} Q_L^{j,a}$$

- 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

- Inclusion of quantum corrections is crucial to assess the viability of a given EFT and it induces correlations to other observables.

  Scalar/tensor operators can generate large $\mathcal{B}(h \to \tau\tau)$ and $(g-2)_\tau$

- We propose a minimalistic model to accommodate the $B$-physics anomalies. Our model is GUT inspired and allows for unification with only two light LQs.

  Yukawas remain perturbative after 1-loop running to $\Lambda_{\mathrm{GUT}}$

- Model passes all constraints and offers several predictions to be tested at Belle-II and LHC(b).

  $$2 \times 10^{-7} \lesssim \mathcal{B}(B \to K\mu\tau) \lesssim 8 \times 10^{-7}$$

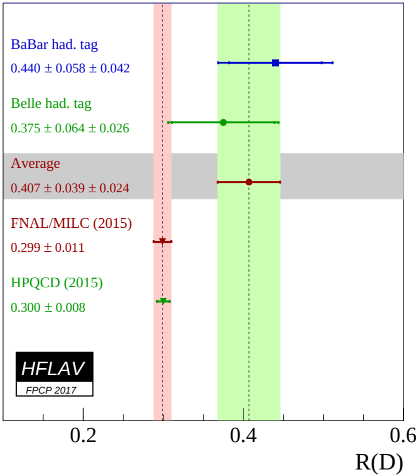
- Building a concrete model to simultaneously explain $R_{K^{(*)}}$ and $R_{D^{(*)}}$ remains a very challenging task.

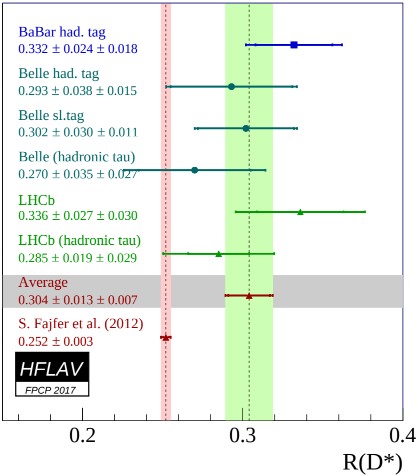
  Data-driven model building!

**Thank you!**

*This project has received support from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 674896.*

# Back-up




- $3.9\sigma$ 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)!

## (i) $R_{D^{(*)}} = \mathcal{B}(B \to D^{(*)}\tau\bar{\nu})/\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})$

Theory (tree-level in SM)

- $R_D$: lattice QCD at $q^2 \neq q^2_{\text{max}}$ $(w > 1)$ available for both leading (vector) and subleading (scalar) form factors [MILC 2015, HPQCD 2015]

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

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

- $R_{D^*}$: lattice QCD at $q^2 \neq q^2_{\text{max}}$ 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?)*

## SM predictions for $R_{D^{(*)}}$

| Ref. | $R_D$ | $R_{D^*}$ | dev. $(R_D)$ | dev. $(R_{D^*})$ |
|---|---|---|---|---|
| Exp. [HFLAV] | $0.41(5)$ | $0.304(15)$ | – | – |
| LQCD [FLAG] | $0.300(8)$ | – | $2.3\sigma$ | – |
| Fajfer et al. '12 | $0.296(16)$ | $0.252(3)$ | $2.3\sigma$ | $3.4\sigma$ |
| Bigi et al. '16 | $0.299(3)$ | – | $2.3\sigma$ | – |
| Bigi et al. '17 | – | $0.260(8)$ | – | $2.6\sigma$ |
| Bernlochner et al. '17 | $0.298(3)$ | $0.257(3)$ | $2.4\sigma$ | $3.1\sigma$ |

- Larger errors in [Bigi et al.] for $R_{D^*}$. Good agreement for $R_D$.
- LQCD determination of $A_0(q^2)$ would be very helpful.
- Soft photon corrections: first steps in [de Boer et al. 2018] Disentangling structure dependent terms, important!? – More work needed.

[Feruglio, Paradisi, OS. 1806.10155]

$$\frac{R_{D^{(*)}}}{R_{D^{(*)}}^{\rm SM}} = 1 + a_S^{D^{(*)}}\,|g_S^\tau|^2 + a_P^{D^{(*)}}\,|g_P^\tau|^2 + a_T^{D^{(*)}}\,|g_T^\tau|^2$$

$$+\, a_{SV_L}^{D^{(*)}}\,\mathrm{Re}\,[g_S^\tau] + a_{PV_L}^{D^{(*)}}\,\mathrm{Re}\,[g_P^\tau] + a_{TV_L}^{D^{(*)}}\,\mathrm{Re}\,[g_T^\tau]\;,$$

| Decay mode | $a_S^M$ | $a_{SV_L}^M$ | $a_P^M$ | $a_{PV_L}^M$ | $a_T^M$ | $a_{TV_L}^M$ |
|---|---|---|---|---|---|---|
| $B \to D$ | $1.08(1)$ | $1.54(2)$ | $0$ | $0$ | $0.83(5)$ | $1.09(3)$ |
| $B \to D^*$ | $0$ | $0$ | $0.0473(5)$ | $0.14(2)$ | $17.3(16)$ | $-5.1(4)$ |

## Our EFT setup

[Feruglio, Paradisi, OS. 1806.10155]

$$\mathcal{L}^0_{\rm NP} = \frac{C_{S_L}^{prst}}{\Lambda^2}\,\big[\mathcal{O}^{(1)}_{\ell equ}\big]_{prst} + \frac{C_{T}^{prst}}{\Lambda^2}\,\big[\mathcal{O}^{(3)}_{\ell equ}\big]_{prst} + \text{h.c.}\,,$$

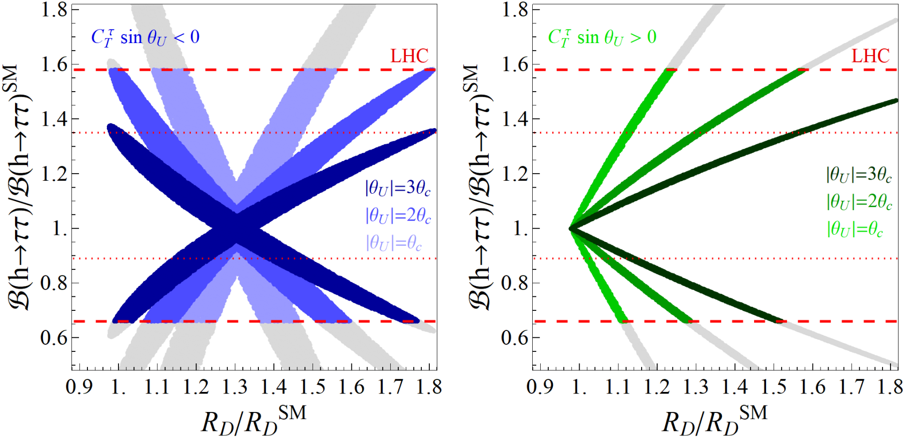
$$\big[\mathcal{O}^{(1)}_{\ell equ}\big]_{prst} = \big(\overline{L'_p}^{a} e'_{rR}\big)\varepsilon_{ab}\big(\overline{Q'_s}^{b} u'_{tR}\big)\,,$$

$$\big[\mathcal{O}^{(3)}_{\ell equ}\big]_{prst} = \big(\overline{L'_p}^{a}\sigma_{\mu\nu} e'_{rR}\big)\varepsilon_{ab}\big(\overline{Q'_s}^{b}\sigma^{\mu\nu} u'_{Rt}\big)\,,$$

with $C_i^{prst} = C_i\,\delta_{p3}\,\delta_{r3}\,\delta_{s3}\,\delta_{t3}$

## Flavor to mass basis rotations:

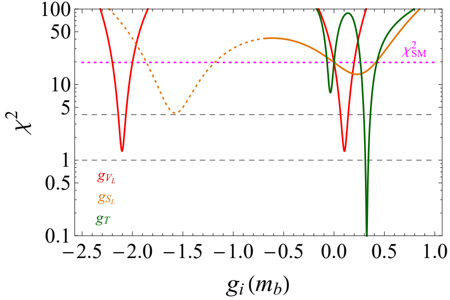
$$U_{R,u} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \cos\theta_U & -\sin\theta_U \\ 0 & \sin\theta_U & \cos\theta_U \end{pmatrix}\,, \qquad\qquad U_{R,d} = U_{R,\ell} = \mathbb{1}\,.$$

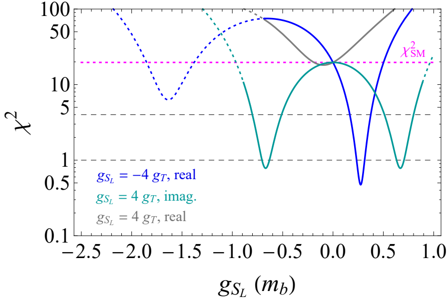

$C_T^\tau \sin\theta_U < 0$
LHC
$|\theta_U|=3\theta_c$
$|\theta_U|=2\theta_c$
$|\theta_U|=\theta_c$
$\mathcal{B}(h\to\tau\tau)/\mathcal{B}(h\to\tau\tau)^{SM}$
$R_D/R_D^{SM}$
$C_T^\tau \sin\theta_U > 0$
LHC
$|\theta_U|=3\theta_c$
$|\theta_U|=2\theta_c$
$|\theta_U|=\theta_c$
$\mathcal{B}(h\to\tau\tau)/\mathcal{B}(h\to\tau\tau)^{SM}$
$R_D/R_D^{SM}$

## Leptoquarks for $R_{K^{(*)}}$ and $R_{D^{(*)}}$

| Model | $R_{K^{(*)}}$ | $R_{D^{(*)}}$ | $R_{K^{(*)}}$ & $R_{D^{(*)}}$ |
|---|---|---|---|
| $S_1$ | ✗* | ✓ | ✗* |
| $R_2$ | ✗* | ✓ | ✗ |
| $\widetilde{R_2}$ | ✗ | ✗ | ✗ |
| $S_3$ | ✓ | ✗ | ✗ |
| $U_1$ | ✓ | ✓ | ✓ |
| $U_3$ | ✓ | ✗ | ✗ |

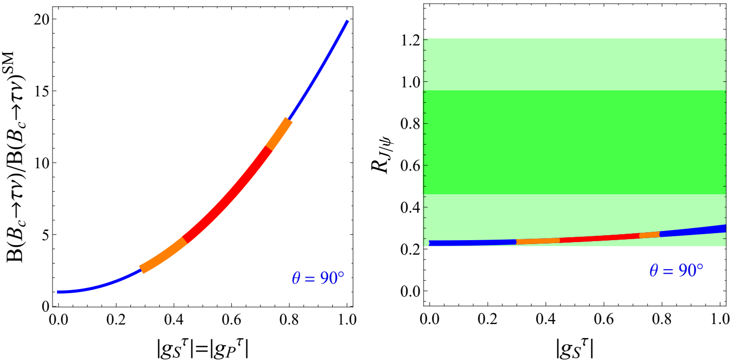
[Angelescu, Becirevic, Faroughy, OS. 2018]




[Angelescu, Becirevic, Faroughy, OS. 2018]

# Results – a few predictions




✓ OK with $\mathcal{B}(B_c \to \tau\nu) < 30\%$ [Alonso et al 2017], and $\lesssim 10\%$ [Akeroyd et al 2017]

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

[Becirevic, Leljak,Melic, OS. 2018]

# Model arXiv:1806.10155

Two scalar leptoquarks

- In flavor basis

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

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

and assume

$$\underline{y_R = y_R^T \qquad y = -y_L}$$

- In mass basis

$$\begin{aligned}\mathcal{L} \supset\ & (V_{\text{CKM}}\, y_R\, E_R^\dagger)^{ij}\ \bar{u}'_{Li} \ell'_{Rj} R_2^{(5/3)} + (y_R\, E_R^\dagger)^{ij}\ \bar{d}'_{Li} \ell'_{Rj} R_2^{(2/3)} \\ & + (U_R\, y_L\, U_{\text{PMNS}})^{ij}\ \bar{u}'_{Ri} \nu'_{Lj} R_2^{(2/3)} - (U_R\, y_L)^{ij}\ \bar{u}'_{Ri} \ell'_{Lj} R_2^{(5/3)} \\ & - (y\, U_{\text{PMNS}})^{ij}\ \bar{d}'^{C}_{Li} \nu'_{Lj} S_3^{(1/3)} - \sqrt{2}\, y^{ij}\ \bar{d}'^{C}_{Li} \ell'_{Lj} S_3^{(4/3)} \\ & + \sqrt{2} (V_{\text{CKM}}^*\, y\, U_{\text{PMNS}})_{ij}\ \bar{u}'^{C}_{Li} \nu'_{Lj} S_3^{(-2/3)} - (V_{\text{CKM}}^*\, y)_{ij}\ \bar{u}'^{C}_{Li} \ell'_{Lj} S_3^{(1/3)} + \text{h.c.}\end{aligned}$$

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

$$\begin{aligned}\mathcal{L} \supset\ & (V_{\rm CKM}\, y_R\, E_R^\dagger)^{ij}\, \bar{u}'_{Li}\ell'_{Rj} R_2^{(5/3)} + (y_R\, E_R^\dagger)^{ij}\, \bar{d}'_{Li}\ell'_{Rj} R_2^{(2/3)} \\ & + (U_R\, y_L\, U_{\rm PMNS})^{ij}\, \bar{u}'_{Ri}\nu'_{Lj} R_2^{(2/3)} - (U_R\, y_L)^{ij}\, \bar{u}'_{Ri}\ell'_{Lj} R_2^{(5/3)} \\ & - (y\, U_{\rm PMNS})^{ij}\, \bar{d}'^{C}_{Li}\nu'_{Lj} S_3^{(1/3)} - \sqrt{2}\, y^{ij}\, \bar{d}'^{C}_{Li}\ell'_{Lj} S_3^{(4/3)} \\ & + \sqrt{2}(V^*_{\rm CKM}\, y\, U_{\rm PMNS})_{ij}\, \bar{u}'^{C}_{Li}\nu'_{Lj} S_3^{(-2/3)} - (V^*_{\rm CKM}\, y)_{ij}\, \bar{u}'^{C}_{Li}\ell'_{Lj} S_3^{(1/3)} + \text{h.c.}\end{aligned}$$

and assume

$$y_R = y_R^T \qquad y = -y_L$$

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

Parameters: $m_{R_2}$, $m_{S_3}$, $y_R^{b\tau}$, $y_L^{c\mu}$, $y_L^{c\tau}$ and $\theta$

$$16\pi^2 \frac{\mathrm{d}\log y_R^{b\tau}}{\mathrm{d}\log\mu} = |y_L^{c\mu}|^2 + |y_L^{c\tau}|^2 + \frac{9}{2}|y_R^{b\tau}|^2 + \frac{y_t^2}{2} + \dots$$