Scalar leptoquarks from GUT to the B-anomalies

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In collaboration with

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INFN

elusives
neutrinos, dark matter & dark energy physics

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Motivation

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

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

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

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

This talk: (i) General considerations on leptoquark models

(ii) A viable GUT-inspired model for $R_{D^{(*)}}$ and $R_{K^{(*)}}$.

Why leptoquarks?

Is there a **model of New Physics** to explain these anomalies?

In general: difficult task (many constraints from flavor, LEP, LHC...).

see talks by Baker, Cline, Cox, Crivellin, D'Ambrosio, Faroughy
Greljo, Gripaios, Isidori, Jung, Kosnik, Ligeti, Marzocca
Soni, Shih, Watanabe, Ziegler

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$\Rightarrow$ Scalar and vector **leptoquarks** (LQ) are the **best candidates** so far:

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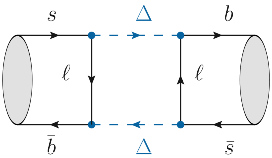
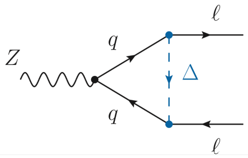
$\Rightarrow$ Scalar and vector **leptoquarks** (LQ) are the **best candidates** so far:

- $\tau \to 3\mu$, $\tau \to \mu\nu\bar{\nu}$ and $\Delta F = 2$ observables are loop-suppressed.

see also [Feruglio et al. '16, '17]





- LHC constraints can be (partially) avoided for 3rd gen LQs.

see talks by Buttazzo and Greljo

NB. *Conclusion mostly driven by* $R_{D^{(*)}}$. see e.g. [Buttazzo et al. '17]

Which leptoquark?

What is the scale of New Physics?

- $R_{D^{(*)}}^{\text{exp}} > R_{D^{(*)}}^{\text{SM}} \quad \Rightarrow \quad \Lambda_{\text{NP}} \lesssim 3$ TeV [perturbative couplings]
- $R_{K^{(*)}}^{\text{exp}} < R_{K^{(*)}}^{\text{SM}} \quad \Rightarrow \quad \Lambda_{\text{NP}} \lesssim 30$ TeV see also [Di Luzio et al. '17]

$R_{D^{(*)}}^{\text{exp}}$ will be the main guideline of my discussion

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

NB. w/o ν_R

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

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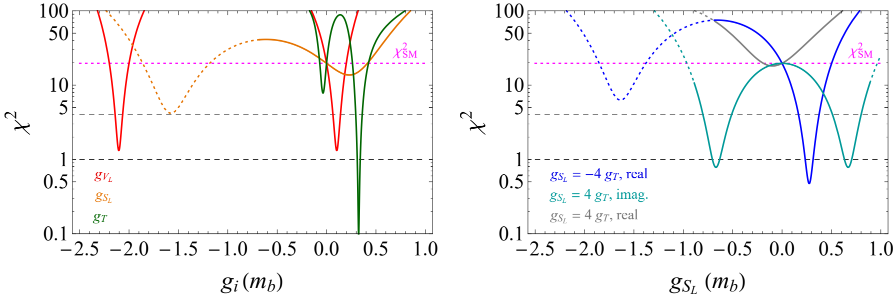
$$+ g_{S_R}(\bar{c}_L b_R)(\bar{\ell}_R\nu_L) + g_{S_L}(\bar{c}_R b_L)(\bar{\ell}_R\nu_L) + g_T(\bar{c}_R\sigma_{\mu\nu}b_L)(\bar{\ell}_R\sigma^{\mu\nu}\nu_L)\Big] + \text{h.c.}$$

Few viable solutions to $R_{D^{(*)}}$:

see also talks by Crivellin, Ligeti and Watanabe



[Angelescu, Becirevic, Faroughy, OS. 1808.08179], see also [Freytsis '15]

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

Leptoquarks for $R_{D^{(*)}}$

NB. w/o ν_R

see also [Dorsner et al. '16]

Model	$g_{\text{eff}}^{b\to c\tau\bar{\nu}}(\mu = m_\Delta)$	$R_{D^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	$g_{V_L},\ g_{S_L} = -4\, g_T$	✓
$R_2 = (3, 2, 7/6)$	$g_{S_L} = 4\, g_T$	✓
$S_3 = (\bar{3}, 3, 1/3)$	g_{V_L}	✗
...	...	...
$U_1 = (3, 1, 2/3)$	$g_{V_L},\ g_{S_R}$	✓
$U_3 = (3, 3, 2/3)$	g_{V_L}	✗
...	...	...

Viable models for $R_{D^{(*)}}$: [Angelescu, Becirevic, Faroughy, OS. 1808.08179]

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

see talk by Watanabe

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

More in talks by Di Luzio, Kosnik and Watanabe

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗*	✗*
$R_2 = (3, 2, 7/6)$	✓	✗*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

[Angelescu, Becirevic, Faroughy, OS. 1808.08179]

see also [Barbieri et al. '15, Buttazzo et al. '17]

- 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).
  ⇒ 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):
  ⇒ 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

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

- 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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  [Angelescu, Becirevic, Faroughy and OS. 1808.08179]

- In flavor basis

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

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

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

- In mass-eigenstates basis

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

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

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

and assume

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

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

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

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

- $b \to c\tau\bar{\nu}$: **NB**. $\Lambda_{\rm NP}/g_{\rm NP} \approx 1$ TeV

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

- $b \to s\mu\mu$: **NB**. $\Lambda_{\rm NP}/g_{\rm NP} \approx 30$ TeV

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

- Δm_{B_s}:

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

⇒ 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]

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

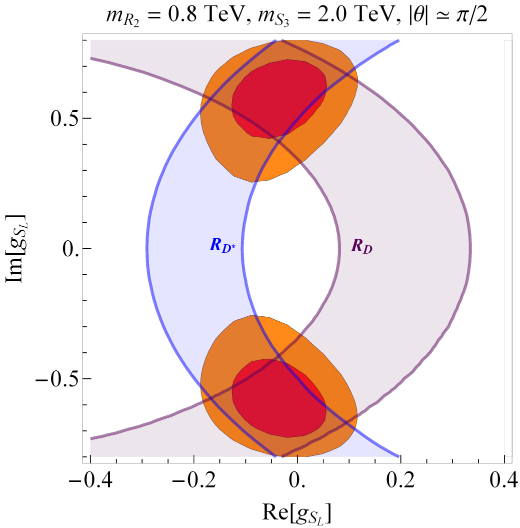
- $\mathcal{B}(\tau \to \mu\phi) < 8.4 \times 10^{-8}$ [PDG]
- Loops: $\mathcal{B}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$ [PDG]
- Loops: $\Delta m_{B_s}^{\mathrm{exp}} = 17.7(2)\ \mathrm{ps}^{-1}$ [PDG], $\Delta m_{B_s}^{\mathrm{SM}} = (19.0 \pm 2.4)\ \mathrm{ps}^{-1}$ [FLAG 2016]
- Loops: $Z \to \mu\mu$, $Z \to \tau\tau$, $Z \to \nu\nu$ [PDG]

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

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

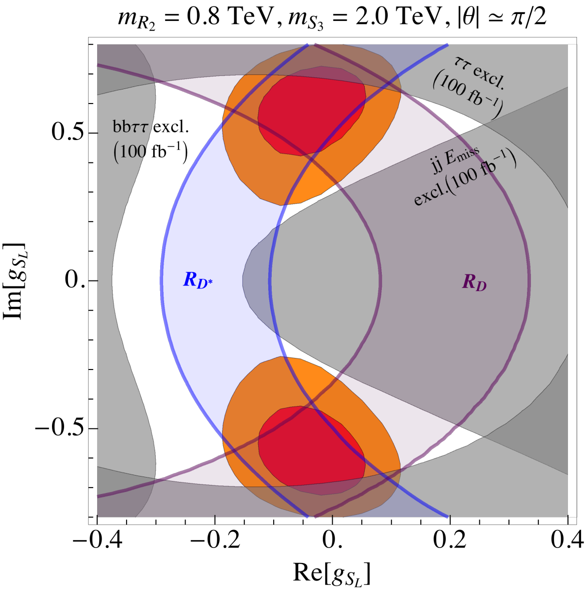
Results and predictions:

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

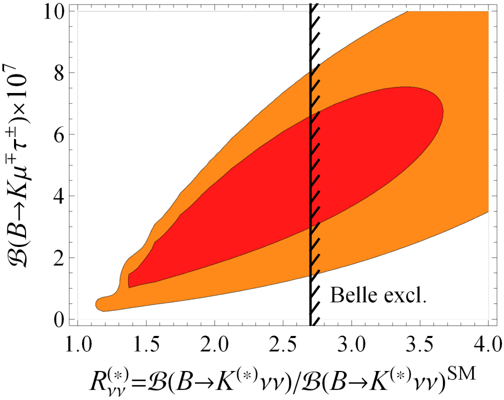


For $\mathrm{Re}[g_{S_L}] = 0$ we get $\mathrm{Im}[g_{S_L}]| = 0.59^{+0.13(+0.20)}_{-0.14(-0.29)}$

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



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. $\mathcal{B}(B \to K^*\mu\tau)/\mathcal{B}(B \to K\mu\tau) \approx 1.8$, $\mathcal{B}(B \to K\mu\tau)/\mathcal{B}(B_s \to \mu\tau) \approx 1.25$

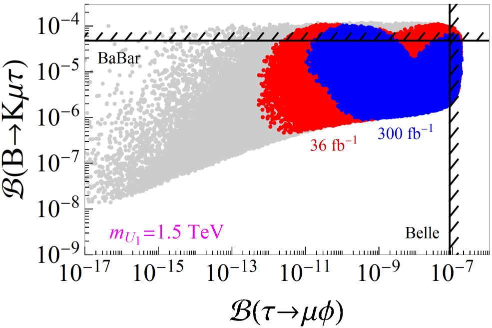
[Becirevic, OS, Zukanovich. 1602.00881]

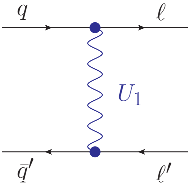
see also [Guadagnoli et al. '15]

[Intermezzo]

[Angelescu, Becirevic, Faroughy and OS. 1808.08179]

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





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

see also [Guadagnoli et al. '15,'18]

- BaBar: $\mathcal{B}(B \to K\mu^{\pm}\tau^{\mp}) < 4.8 \times 10^{-5}$ (90%CL). Can LHCb do better?

Simple and viable $SU(5)$ GUT

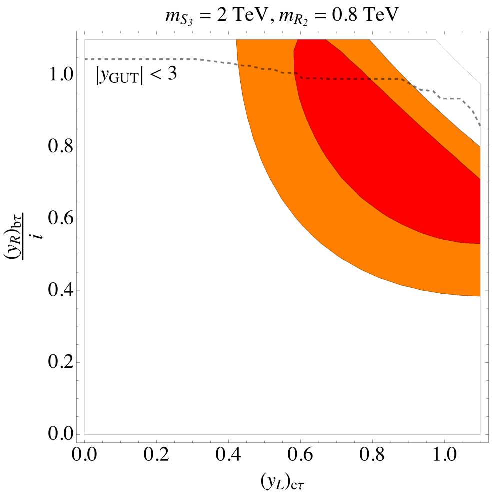
- Choice of Yukawas was biased by $SU(5)$ GUT aspirations
- Scalars: $R_2 \in \underline{\mathbf{45}}, \underline{\mathbf{50}}$, $S_3 \in \underline{\mathbf{45}}$. SM matter fields in $\mathbf{5}_i$ and $\mathbf{10}_i$
- Available operators

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

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

- 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!
- Operators $\mathbf{10}_i \mathbf{10}_j \underline{\mathbf{45}}$ forbidden to prevent proton decay [Dorsner et al 2017]
- 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]

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



$\Rightarrow$ Yukawas remain perturbative after 1-loop running to Λ_{GUT} !

Summary and perspectives

- 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 $b \to s\ell\ell$, but NOT for $b \to c\ell\bar{\nu}$
- Our model is GUT inspired and allows for unification with only two light LQs.
  Yukawas remain perturbative after 1-loop running to Λ_{GUT}
- Our model offers several predictions to be tested at Belle-II and LHC(b).
  e.g., $2 \times 10^{-7} \lesssim \mathcal{B}(B \to K\mu\tau) \lesssim 8 \times 10^{-7}$
- Results of the direct LHC searches might soon become relevant too.
  Opportunities for direct searches at LHC!
- 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!

Thank you!

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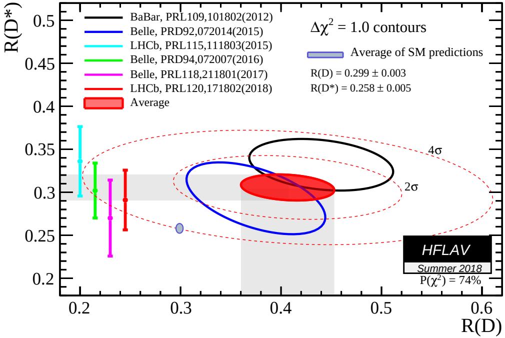
Back-up

(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 Koppenburg



- R_D: B-factories $[\approx 2\sigma]$
- R_{D^*}: B-factories and LHCb $[\lesssim 3\sigma]$; dominated by BaBar
- LHCb confirmed tendency $R_{J/\psi}^{\mathrm{exp}} > R_{J/\psi}^{\mathrm{SM}}$, 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 $(R_{D_s}, R_{D_s^*}, R_{\Lambda_c} \ldots)$

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

Theory (tree-level in SM)

See talk by Ligeti

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

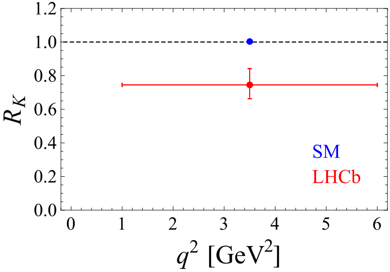
  *Use **decay angular distributions** measured at B-factories to fit the **leading form factor** $[A_1(q^2)]$ and extract **two others as ratios** wrt $A_1(q^2)$. All other ratios from HQET (NLO in $1/m_{c,b}$) [Bernlochner et al 2017] but with more generous error bars (truncation errors?)*

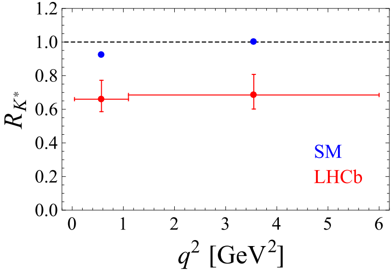
  see also [Bigi et al. '17]

(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 Jager, Koppenburg

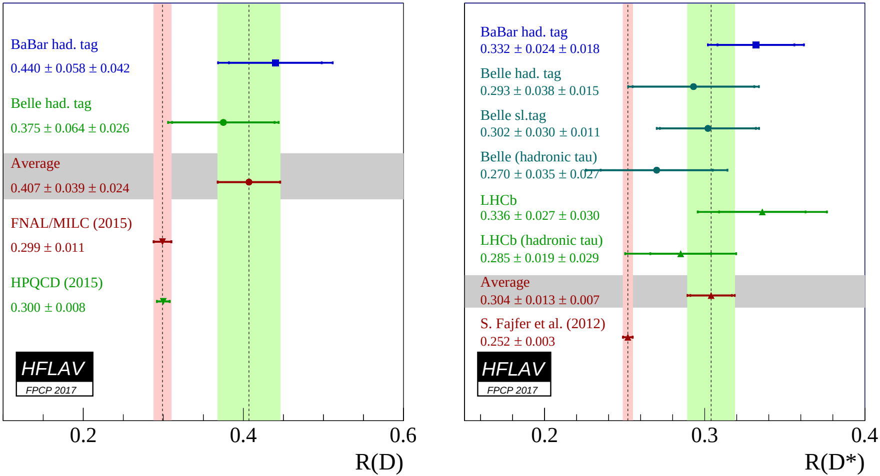




$\Rightarrow$ Needs confirmation from Belle-II!

Theory (loop induced in SM)

- Hadronic uncertainties cancel to a large extent [Hiller et al. '03]
  $\Rightarrow$ Clean observables! [*working below the narrow $c\bar{c}$ resonances*]
- QED corrections important, $R_{K^{(*)}} = 1.00(1)$ [Bordone et al. '16]



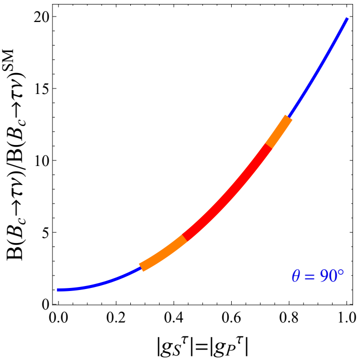
- 3.9σ combined deviation from the SM [theory error under control?]
- Discrepancy driven by oldest exp. results (BaBar and LHCb).
- Needs confirmation from Belle-II (and LHCb run-2)!

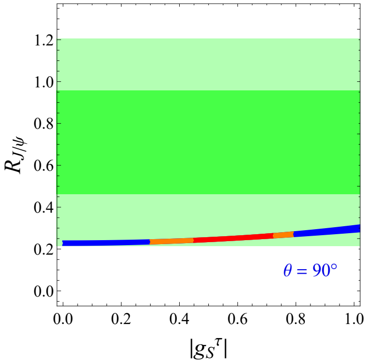
[Feruglio, Paradisi, OS. 1806.10155]

$$\frac{R_{D^{(*)}}}{R_{D^{(*)}}^{\mathrm{SM}}} = 1 + a_S^{D^{(*)}}\,|g_S^\tau|^2 + a_P^{D^{(*)}}\,|g_P^\tau|^2 + a_T^{D^{(*)}}\,|g_T^\tau|^2 + a_{SV_L}^{D^{(*)}}\,\mathrm{Re}\,[g_S^\tau] + a_{PV_L}^{D^{(*)}}\,\mathrm{Re}\,[g_P^\tau] + a_{TV_L}^{D^{(*)}}\,\mathrm{Re}\,[g_T^\tau]\,,$$

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	$0.0473(5)$	$0.14(2)$	$17.3(16)$	$-5.1(4)$

Results – a few predictions





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

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

[Becirevic, Leljak,Melic, OS. '18]

More exp. information is needed to distinguish among them!

i) Many angular observables (e.g., $A_{\rm fb}$, polarization asymmetries)

[Becirevic et al. '16]

First measurements:

- $P_\tau(D^*)^{\rm exp} = -0.38 \pm 0.51^{+0.21}_{-0.16}$ [Belle '17]
- $F_L(D^*)^{\rm exp} = 0.60 \pm 0.08 \pm 0.03$ [Belle '18] see talk by Adamczyk at CKM

ii) Other LFUV ratios:

- $R_{J/\psi}$, R_{D_s}, $R_{D_s^*}$, $R_{\Lambda_c}\dots$

iii) Leptonic observables (via RGE effects)

- $g_{V_L} \Rightarrow$ Corrections to $Z \to \ell\ell$, $\tau \to \mu\nu\bar{\nu}$ [Feruglio et al. 2015]
- g_{S_L} and $g_T \Rightarrow$ Enhanced contributions to $H \to \tau\tau$ and $(g-2)_\tau$

[Feruglio, Paradisi, OS. 1806.10155]

Dekens et al. '18

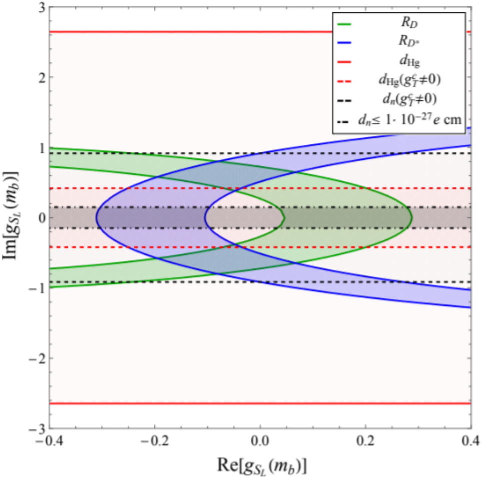


Figure 11: Contours in the Re $g_{S_L}(m_b)$-Im $g_{S_L}(m_b)$ plane. The R_D and R_D^* contours (at 90% C.L.) are shown in green and blue, respectively. The current constraints from from the Hg EDM is shown in red, while the dark-red band is a projection for a future neutron EDM measurement assuming an order of magnitude improvement.