Scalar leptoquarks from GUT to accommodate the B-physics anomalies

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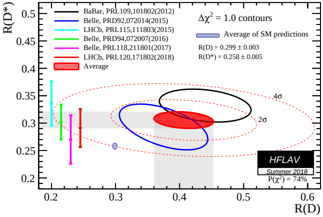
- Lepton (flavor) universality violation in $V_{cb}^{(\tau)}$

	HFLAV	SM	dev
R_{D^*}	0.306(15)	0.252(3)	3.6σ
R_D	0.407(46)	0.300(8)	2.3σ
$R_{D^{(*)}}$			$\sim \mathbf{4\sigma}$

- $R_{J/\psi}$ measurement points in the same direction:

$$0.20 < R_{J/\psi} < 0.39^{1} \text{ Vs.}$$

$$R(J/\psi)^{\rm LHCb} = 0.71(17)(18)$$



[1] Cohen et al., '18
[2] Isidori et al. '16

Lepton universality violation in charged and neutral currents

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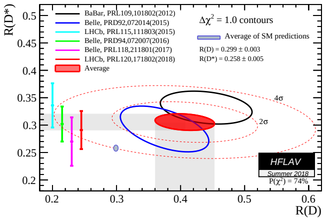
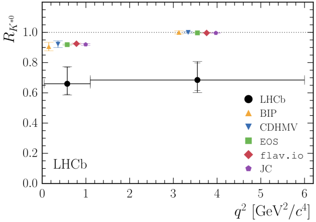
- LFUV in $b \to s\ell^+\ell^-$

	LHCb	SM	dev.
R_K	0.745(97)	$1.00(1)^2$	2.6σ
$R_{K^*\rm low}$	0.660(113)	$0.906(28)^2$	2.1σ
R_{K^*}	0.685(122)	$1.00(1)^2$	2.6σ
			$\sim \mathbf{4\sigma}$





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Implications for New Physics

- $R_{K^{(*)}} \sim 10\%$ modification of the 1-loop GIM-suppressed amplitude
- $R_{D^{(*)}} \sim 10\%$ effect on the tree-level W exchange V_{cb}.
- *Can the two effects have common NP origin?*

→ What are typical mass scales of NP addressing the two LFUV phenomena? (Assume NP contributes to the SM operator with coupling 1)

$R_{K^{(*)}}$ $(b \to s\mu\mu)$

- SM: $\approx \frac{G_F V_{ts} V_{tb} \alpha}{(4\pi)} (\bar{s}\gamma^\mu P_L b)(\bar{\mu}\gamma_\mu \mu)$

⇒ 1-loop NP: $\frac{1}{(4\pi)^2 \Lambda^2} \Rightarrow \Lambda \approx 3\ \mathrm{TeV}$

⇒ Tree-level NP: $C_9 \sim \frac{1}{\Lambda^2} \Rightarrow \Lambda \approx 30\ \mathrm{TeV}$

$R_{D^{(*)}}$ $(b \to c\tau\nu)$

- SM: $\frac{G_F V_{cb}}{\sqrt{2}} (\bar{c}b)_{V-A} (\bar{\ell}\nu)_{V-A}$

⇒ Tree-level NP: $\frac{1}{\Lambda^2} \Rightarrow \Lambda \approx 3\ \mathrm{TeV}$

How to explain different sizes of the effects?

1. Different scales of NP for $R_{K^{(*)}}$ and $R_{D^{(*)}}$
2. Loop ($R_{K^{(*)}}$) Vs. tree ($R_{D^{(*)}}$)
3. Suppression of NP couplings in $R_{K^{(*)}}$ compared to $R_{D^{(*)}}$

Identifying a viable model

- Effective theory analysis focused on left-handed current operators

$$\frac{C_1}{\Lambda^2}(\bar{Q}_3\gamma^\mu Q_3)(\bar{L}_3\gamma_\mu L_3) + \frac{C_3}{\Lambda^2}(\bar{Q}_3\boldsymbol{\sigma}\gamma^\mu Q_3)\cdot(\bar{L}_3\boldsymbol{\sigma}\gamma_\mu L_3)$$

[Buttazzo et al '17, Bhattacharya et al '14, Feruglio et al '16]

- As a single mediator particle, vector leptoquark $U_1(3,1,2/3)$ is singled out [Buttazzo et al '17]
- UV complete setting needed (Pati-Salam, 4321 model) [Assad et al '17, Bordone et al '17,18, Greljo et al '18, Di Luzio et al '17, Blanke, Crivellin et al '18, Calibbi et al '17]

- Scalar LQs are not UV sensitive, however single LQ does not work
- Two scalar LQs can generate left-handed operators and solve the B-anomalies [Crivellin '17]
- Two scalar LQs can also contribute to alternative Lorentz structures, no UV complete model available

Two light scalar LQ model

- SM + 2 leptoquarks at 1 TeV, guided by $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

$$R_2(3,2,7/6): \qquad Y_R^{ij}\,\bar{Q}'_i \ell'_{Rj} R_2 + Y_L^{ij}\,\bar{u}'_{Ri} \widetilde{R}_2^\dagger L'_j$$

$$\text{mass basis} \rightarrow (V Y_R E_R^\dagger)^{ij}\,\bar{u}_{Li}\ell_{Rj} R_2^{\frac{5}{3}} + (Y_R E_R^\dagger)^{ij}\,\bar{d}_{Li}\ell_{Rj} R_2^{\frac{2}{3}} + (U_R Y_L)^{ij}\,\bar{u}_{Ri}\nu_{Lj} R_2^{\frac{2}{3}} - (U_R Y_L)^{ij}\,\bar{u}_{Ri}\ell_{Lj} R_2^{\frac{5}{3}}$$

$$\text{Assumption:} \qquad Y_R E_R^\dagger = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix}, \qquad U_R Y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

$$S_3(\bar{3},3,1/3): \qquad Y^{ij}\,\bar{Q}_i'^C i\tau_2 (\tau_k S_3^k) L'_j$$

$$\text{mass basis} \rightarrow -(Y)^{ij}\,\bar{d}_{Li}^C \nu_{Lj} S_3^{\frac{1}{3}} + \sqrt{2}(V^* Y)^{ij}\,\bar{u}_{Li}^C \nu_{Lj} S_3^{-\frac{2}{3}} \; \sqrt{2} Y^{ij}\,\bar{d}_{Li}^C \ell_{Lj} S_3^{\frac{4}{3}} - (V^* Y)^{ij}\,\bar{u}_{Li}^C \ell_{Lj} S_3^{\frac{1}{3}}$$

$$\text{GUT relation}: \qquad Y = -Y_L = -\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

[0] Free parameters: m_{R_2}, m_{S_3}, complex $y_R^{b\tau}$, $y_L^{c\mu}$, $y_L^{c\tau}$, θ

GUT framework for R_2 and S_3

- $SU(5)$ unified gauge group
- fermions

$$\bar{\mathbf{5}}_i = (L, \bar{d}_R)_i, \qquad \mathbf{10}_i = (\bar{e}_R, \bar{u}_R, Q)_i$$

- At unification scale M_{GUT} gauge bosons of $SU(5)$ (vector leptoquarks) couple leptons and quarks
- Scalar representations contain scalar leptoquarks:
  - **24** breaks $SU(5)$, $M_{X,Y} \sim g_{\mathrm{GUT}} M_{\mathrm{GUT}}$
  - **45** contains R_2 and S_3
  - **50** contains R_2'
- Yukawa couplings

$$a^{ij}\mathbf{10}_i\bar{\mathbf{5}}_j\,\mathbf{45} \qquad b^{ij}\mathbf{10}_i\mathbf{10}_j\,\mathbf{50} \qquad (b = b^T, \text{ symmetric in flavor space})$$

- R_2 and R_2' mix via $\mu\mathbf{45}\,\overline{\mathbf{50}}\,\mathbf{24}$ into light R_2 and heavy R_{2H}.

GUT framework for R_2 and S_3

- Matching onto effective theory results in the couplings considered in flavor and LHC

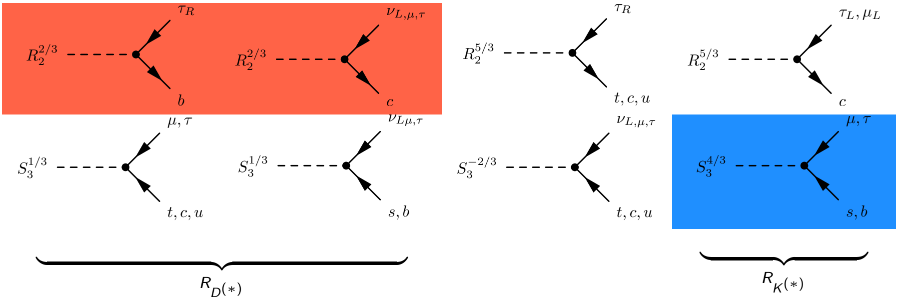
$$Y_R^{ij}\,\bar{Q}'_i \ell'_{Rj} R_2 + Y_L^{ij}\,\bar{u}'_{Ri} \widetilde{R}_2^{\dagger} L'_j + Y^{ij}\,\bar{Q}'^{C}_i i\tau_2 (\tau_k S_3^k) L'_j$$

where

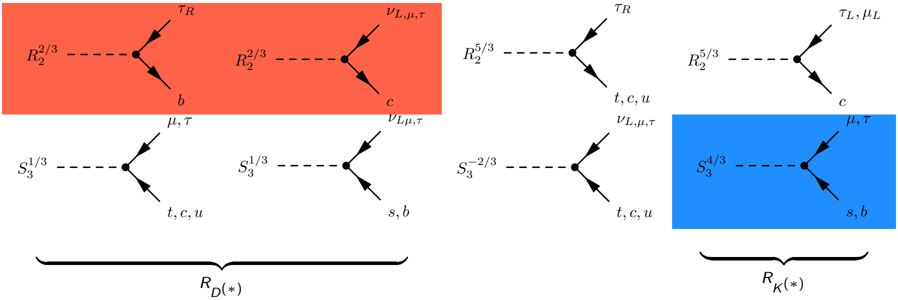
$$Y_L = a\cos\phi \qquad Y_R = b\sin\phi, \qquad Y = -\frac{a}{\sqrt{2}}$$

- Assume $\phi = \pi/2$ (assumption is not crucial to further analysis)
- Proton destabilizing diquark interactions $\bar{Q}\bar{Q}S_3$ ($\mathbf{10}_i\mathbf{10}_j\mathbf{45}$) can be forbidden.[Doršner et al, 2017]

Charged currents



Charged currents



$R_{D(*)}$

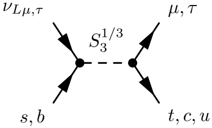
Dominant contribution by R_2 via scalar and tensor interactions

$$\mathcal{H} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[g_{S_L} (\bar{c}_R b_L)(\bar{\tau}_R \nu_L) + g_T (\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu} \nu_L) \right]$$

$$g_{S_L} = 4 g_T = \frac{y_L^{c\nu} \, y_R^{b\tau\,*}}{4\sqrt{2}\, m_{R_2}^2 \, G_F V_{cb}} \qquad (g_{S_L}(m_b) \approx 7 g_T(m_b))$$

- Scalar and tensor $B \to D$ form factors from lattice QCD [HPQCD ‘15, MILC ‘15]
- $B \to D^*$ FFs extracted from exp. spectra using the heavy quark symm. [Bernlochner et al‘18, HFLAV]

- $b \to c\tau\nu$ is the *only* charged-current affected by R_2
  - $B_c \to \tau\nu$ taken into account
- Leptoquark state S_3 affects many charged currents via charge 1/3 component:

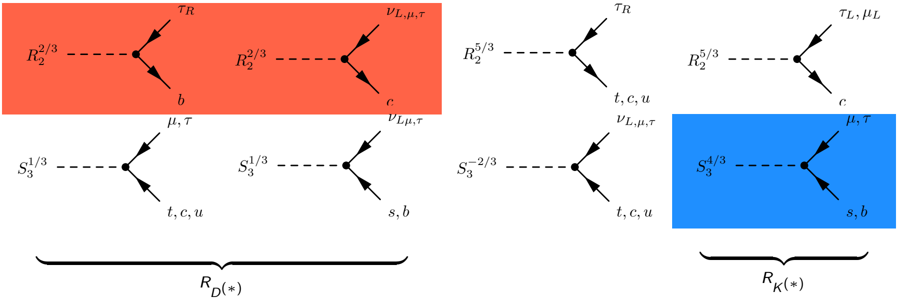


We consider the most relevant constraints:

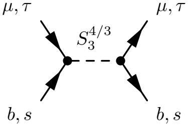
  - $R^{\mu/e}_{D^{(*)}} = \mathcal{B}(B \to D^{(*)}\mu\bar{\nu})/\mathcal{B}(B \to D^{(*)}e\bar{\nu})$
  - $B \to \tau\nu$
  - $\mathcal{B}(K \to e\nu)/\mathcal{B}(K \to \mu\nu)$
  - $\mathcal{B}(\tau \to K\nu)/\mathcal{B}(K \to e\nu)$

$R_{K^{(*)}}$ and neutral currents

- Explained by the $S_3^{4/3}$ charge eigenstate



- $S_3^{4/3}$ couples to left-handed fermions



- Left-handed current operators with μ and τ

$$\mathcal{H}_{\text{eff}}^{b\to sll} = -\frac{4G_F\lambda_t}{\sqrt{2}} \sum_{i=7,9,10} C_i(\mu)\mathcal{O}_i(\mu)$$

$$\mathcal{O}_{9(10)} = \frac{e^2}{(4\pi)^2} \left(\bar{s}_L\gamma_\mu b_L\right)\left(\bar{l}\gamma^\mu(\gamma^5)l\right)$$

$$\delta C_9^{\mu\mu} = -\delta C_{10}^{\mu\mu} = \frac{\pi v^2}{\lambda_t\alpha_{\text{em}}} \frac{y^{b\mu}\left(y^{s\mu}\right)^*}{m_{S_3}^2} = \frac{\pi v^2}{\lambda_t\alpha_{\text{em}}} \frac{\sin 2\theta \left(y_L^{c\mu}\right)^2}{2m_{S_3}^2}$$

- $\sin 2\theta$ and large mass supresses the S_3 effect in $R_{K^{(*)}}$
- Use constraint on $\delta C_9 = -\delta C_{10}$ determined from clean observables: $R_{K^{(*)}}$, $B_s \to \mu^+\mu^-$

$$\delta C_9^{\mu\mu} \in (-0.85, -0.50)^1$$

[1] In agreement with global analyses of $b \to s\mu\mu$ observables. [Capdevilla et al '17, ...]

Neutral current constraints

- $B_s - \bar{B}_s$, Δm_s constraint, suppressed by θ [S_3]

$$\Delta m_s^{\mathrm{S}_3} \sim \sin^2 2\theta \left[(y_L^{c\mu})^2 + (y_L^{c\tau})^2\right]^2 / m_{S_3}^2$$

- $\mathcal{B}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$ [S_3 and R_2]
- $Z \to \ell\ell$ constraints at LEP [S_3 and R_2]

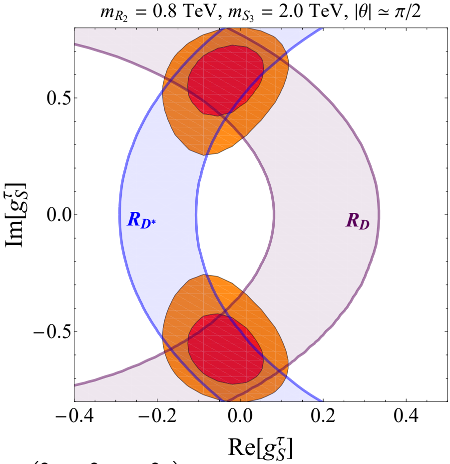
$$\frac{g_V^\tau}{g_V^e} = 0.959(29), \qquad \frac{g_A^\tau}{g_A^e} = 1.0019(15), \qquad \frac{g_V^\mu}{g_V^e} = 0.961(61), \qquad \frac{g_A^\mu}{g_A^e} = 1.0001(13)$$

- $\mathcal{B}(\tau \to \mu\phi) \sim \cos^4\theta (y_L^{c\mu} y_L^{c\tau})^2 / m_{S_3}^4 < 8.4 \times 10^{-8}$, resolves $\theta = 0, \pi$ degeneracy [S_3]
- Small effect in $(g-2)_\mu$

- We *predict* the S_3 contribution to $R_{\nu\nu}^{(*)} = \mathcal{B}(B \to K^{(*)}\nu\nu)/\mathcal{B}(B \to K^{(*)}\nu\nu)_{\mathrm{SM}}$ and compare it with $R_{\nu\nu}^{(*)} < 2.7$ [Belle '17]

Flavor coupling analysis

- Perform a fit with fixed $m_{R_2} = 0.8$ TeV, $m_{S_3} = 2$ TeV, variables $y_L^{c\mu}$,$y_L^{c\tau}$, $\mathrm{Re}\, y_R^{b\tau}$, $\mathrm{Im}\, y_R^{b\tau}$, mixing angle θ
- Larger mass m_{S_3} and small $\sin 2\theta$ suppress the effects in neutral currents relative to $R_{D^{(*)}}$
- Degeneracy of minima with $\theta \approx 0, \pi/2$ is broken by $\tau \to \mu\phi$ which selects $\theta \approx \pi/2$. $\Rightarrow$ S_3 couplings to s-quark are suppressed

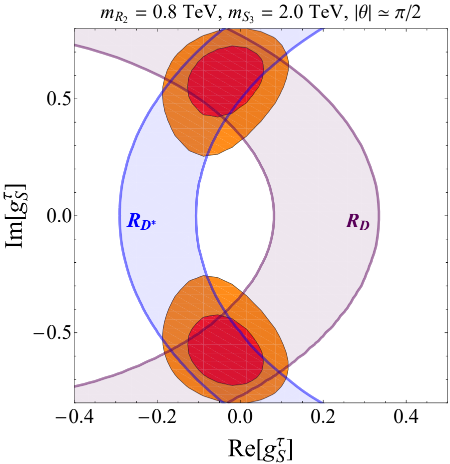


$$Y_{d\ell} \approx -\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 1\\ 0 & -1 & 0\end{pmatrix}\begin{pmatrix}0 & 0 & 0\\ 0 & y_L^{c\mu} & y_L^{c\tau}\\ 0 & 0 & 0\end{pmatrix} \approx \begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & y_L^{c\mu} & y_L^{c\tau}\end{pmatrix}$$

Flavor coupling analysis

- Complex g_S^τ needed in order to reconcile R_D and R_{D^*}. Imaginary g_S^τ has strictly positive effect on $R_{D^{(*)}}$.

- SM point is excluded at 3.8σ (5 degrees of freedom)
- Both $R_{D^{(*)}}$ and $R_{K^{(*)}}$ anomalies are reduced to $< 1\sigma$ level



[Becirevic, Dorsner, Fajfer, Faroughy, NK, Sumensari, 1806.05689]

Perturbativity

- Couplings defined at scale 1 TeV, renormalized with scale[2]

$$16\pi^2 \frac{d \ln y_R^{b\tau}}{d \ln \mu} = |y_L^{c\mu}|^2 + |y_L^{c\tau}|^2 + \frac{9}{2}|y_R^{b\tau}|^2 + \frac{1}{2}y_t^2 + \dots$$

- Require Yukawa couplings of the two LQs to remain perturbative to the unification scale 5×10^{15} GeV

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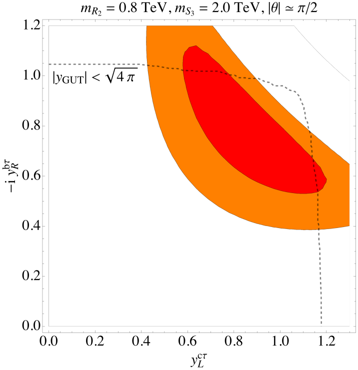

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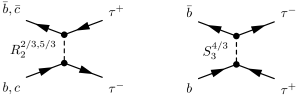
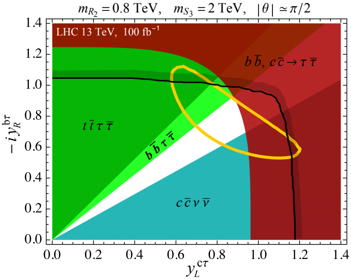
LHC constraints

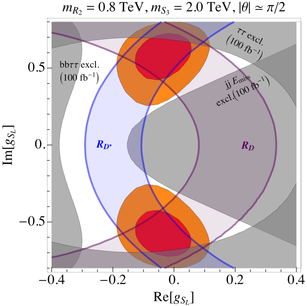
- t-channel $pp \to \tau^+\tau^-$. Dominated by R_2, S_3 only from b-quarks



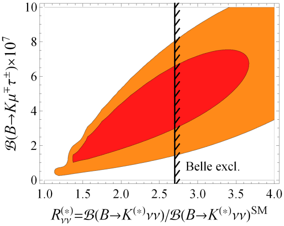
- Constrained by searches for heavy $\tau\tau$ resonance [ATLAS, JHEP 1801, 055]

- Leptoquark pair production bounds the R_2 mass





- LFV and 2ν modes in reach of future experiments
- Correlation between LFV observables



- $\mathcal{B}(B \to K\nu\bar{\nu}) \gtrsim 1.5 \times \mathcal{B}(B \to K\nu\bar{\nu})_{\rm SM}$. Not included in the fit. $\to$ To be improved by Belle 2
- LFV decays
  - $\mathcal{B}(\tau \to \mu\gamma) > 1.5 \times 10^{-8}$
  - $\mathcal{B}(B \to K\mu^\pm\tau^\mp) \in [1.1, 6.5] \times 10^{-7}$. Current bound 4.8×10^{-5} [BaBar '12]
  - $\mathcal{B}(B \to K^*\tau\mu) \approx 1.9 \times \mathcal{B}(B \to K\mu\tau)$
  - $\mathcal{B}(B_s \to \tau\mu) \approx 0.9 \times \mathcal{B}(B \to K\mu\tau)$
  - All LFV limits will be improved by LHCb and Belle 2

Conclusion

- Presented model with two light leptoquarks, $R_2(3, 2, 7/6)$ and $S_3(\bar{3}, 3, 1/3)$
  - R_2 accommodates $R_{D^{(*)}}$ via complex Scalar and Tensor couplings
  - S_3 accommodates $R_{K^{(*)}}$ via real $C_9 = -C_{10}$
- $SU(5)$ GUT framework connects the couplings of R_2 and S_3

- Flavor fit
  - Light $m_{R_2} = 0.8\ \mathrm{TeV}$, requires complex coupling $y_R^{b\tau}$
  - Heavier $S_3 = 2.0\ \mathrm{TeV}$
- Complete resolution of $R_{K^{(*)}}$ and $R_{D^{(*)}}$

- Well-defined GUT completion, perturbative couplings to high scales
- Model consistent with LHC constraints, preferred region can be probed at HL-LHC

- Predicted enhanced LFV signals in $\tau\mu$ sector as well as enhanced $b \to s\nu\bar{\nu}$ modes
- Interesting target for future Belle 2 and LHCb searches