A viable scenario to accommodate current $B$-physics anomalies (and does more)

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More intro and extra-discussion in today talks by Greljo, Alonso, Fuentes and Nardecchia

\[ R_{D(*)} = \frac{\mathcal{B}(B \to D(*)\tau\bar{\nu})}{\mathcal{B}(B \to D(*)\ell\bar{\nu})} \quad \ell \in (e,\mu) \quad \& \quad R_{D(*)}^{\text{exp}} > R_{D(*)}^{\text{SM}} \]

**Experiment**

- **\( R_D \):** \( B \)-factories \( \sim 2\sigma \); needs confirmation from Belle II
- **\( R_{D^*} \):** \( B \)-factories and LHCb; \( \lesssim 3\sigma \) dominated by BaBar; needs confirmation from Belle II
- **\( R_{J/\psi} \):** \( B_c \to J/\psi\tau\bar{\nu})/B(B_c \to J/\psi\mu\bar{\nu}) \) confirmed tendency
  \[ R_{J/\psi}^{\text{exp}} > R_{J/\psi}^{\text{SM}}, \text{ LHCb 2017} \]
Introduction and Remarks

Theory (tree-level in SM)

- $R_D$: lattice QCD at $q^2 \neq q_{\text{max}}^2$ ($w > 1$) available for both leading (vector) and subleading (scalar) form factors MILC 2015, HPQCD 2015
- $R_{D^*}$: lattice QCD at $q^2 \neq q_{\text{max}}^2$ not available, scalar form factor $[A_0(q^2)]$ not 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 $A_1(q^2)$, cf. Gambino talk

All other ratios from HQET (NLO in $1/m$) Bernlochner et al 2017 but with more generous error bars (truncation errors?), cf. Papucci talk
\[ R_{K^*} = \frac{\mathcal{B}(B \rightarrow K^*\mu\mu)}{\mathcal{B}(B \rightarrow K^*ee)} \quad \text{and} \quad R_{K(*)}^{\text{exp}} < R_{K(*)}^{\text{SM}} \]

Experiment

- \( R_K \): LHCb 2014 in \( q^2 \in [1, 6] \, \text{GeV}^2 \), \( \sim 2.5\sigma \); need Belle II (!)
- \( R_{K^*} \): LHCb 2017 in \( q^2 \in [1.1, 6] \, \text{GeV}^2 \) and \( q^2 \in (0, 1.1] \, \text{GeV}^2 \), \( \sim 2.5\sigma \); wait for Belle II

Theory (loop induced in SM)

- Hadronic uncertainties cancel to a large extent [working below the narrow \( c\bar{c} \) resonances]
- QED corrections important, \( R_{K(*)} = 1.00(1) \), Bordone et al 2016
Two scalar leptoquarks

- One LQ alone cannot accommodate all $B$-physics anomalies without getting into trouble with other flavor observables
- Prefer scalar to vector LQ to remain minimalistic in terms of new parameters and to be able to compute loops (VLQ - need UV completion)
- In flavor basis

$$
\mathcal{L} \supset y^i_R \bar{Q}_i \ell R_j R_2 + y^i_L \bar{u}_R i L_j \tilde{R}_2^+ + y^{ij}_C \bar{Q}_i^C i \tau_2 (\tau_k S^k_3) L_j + \text{h.c.}
$$

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

- One LQ alone cannot accommodate all $B$-physics anomalies without getting into trouble with other flavor observables
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$$\mathcal{L} \supset y_R^{ij} \bar{Q}_i \ell_R^j R_2 + y_L^{ij} \bar{u}_{Ri} L_j \bar{R}_2^\dagger + y^{ij} \bar{Q}_i^C i\tau_2 (\tau_k S_3^k) L_j + \text{h.c.}$$

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

- In mass eigenstates basis

$$\mathcal{L} \supset (V_{\text{CKM}} y_R^* E_R^\dagger)^{ij} \bar{u}_{L_i} \ell'_R^j R_2^{(5/3)} + (y_R^* E_R^\dagger)^{ij} \bar{d}_{L_i} \ell'_R^j R_2^{(2/3)}$$

$$+ (U_R y_L^* U_{\text{PMNS}})^{ij} \bar{u}_{Ri}^' \nu'^{L_j} R_2^{(2/3)} - (U_R y_L)^{ij} \bar{u}_{Ri}^' \nu'^{L_j} R_2^{(5/3)}$$

$$- (y U_{\text{PMNS}})^{ij} \bar{d}_{L_i}^' C \nu'^{L_j} S_3^{(1/3)} - \sqrt{2} y^{ij} \bar{d}_{L_i}^' C \nu'^{L_j} S_3^{(4/3)}$$

$$+ \sqrt{2} (V_{\text{CKM}}^* y U_{\text{PMNS}})^{ij} \bar{u}_{L_i}^' C \nu'^{L_j} S_3^{(-2/3)} - (V_{\text{CKM}}^* y)^{ij} \bar{u}_{L_i}^' C \ell'^{L_j} S_3^{(1/3)} + \text{h.c.}$$
Model

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

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

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 \( \theta \)

Phenomenology suggests \( \theta \approx \pi/2 \) and \( y_R^{b\tau} \) complex
\( b \to s \ell \ell, R_K, R_{K^*} \)

\[
\mathcal{H}_{\text{eff}} \supset -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=7,8,9,10,P,S,...} \left( C_i(\mu)O_i + C'_i(\mu)O'_i \right)
\]

- Operators relevant to \( b \to s \ell \ell \) are

\[
O_9 = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \quad O_{10} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma^5 \ell)
\]

- Accommodating clean and measured \( b \to s \ell \ell \) observables including \( R_{K^{(*)}} \):

\[
C_9 = -C_{10} = \frac{\pi v^2}{V_{tb} V_{ts}^* \alpha_{\text{em}}} \frac{y_{b\mu} y_{s\mu}^*}{m_{S_3}^2} \quad C_9^\mu = -C_{10}^\mu \in (-0.85, -0.50)
\]

\( \text{Damir B (LPT)} \)
Global analyses suggest $C_9^\mu < 0$, $C_9^e \approx 0$
\[ L_{\text{eff}} = - \frac{4 G_F}{\sqrt{2}} V_{cb} \left[ (1 + g_V)(\bar{u}_L \gamma_\mu d_L)(\bar{\ell}_L \gamma^\mu \nu_L) + g_S(\mu) (\bar{u}_R d_L)(\bar{\ell}_R \nu_L) \right. \\
+ g_T(\mu) (\bar{u}_R \sigma_{\mu\nu} d_L)(\bar{\ell}_R \sigma^{\mu\nu} \nu_L) \left] + \text{h.c.} \right. \\
\]

- Coefficients \( g_i \) in terms of \( y \)-couplings (up-type and down-type quarks):

\[ g_S = 4 \quad g_T = \frac{y_L^{u\ell'} (y^d_R)}{4\sqrt{2} m_{R_2}^2 G_F V_{ud}} \bigg|_{\mu=m_{R_2}} \quad g_V = -\frac{y_{d\ell'} (V y^*)_{u\ell}}{4\sqrt{2} m_{S_3}^2 G_F V_{ud}} \]

\( u \in \{ u, c \}, \ d \in \{ s, b \}, \ \ell^{(i)} \in \{ \mu, \tau \} \). 

NB \( g_V \) is tiny!
Other notable constraints...

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

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

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

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

- Loops: $Z \rightarrow \mu\mu, Z \rightarrow \tau\tau, Z \rightarrow \nu\nu$ [PDG]
  \[ \frac{g^{\tau}_{V}}{g^{e}_{V}} = 0.959(29), \frac{g^{\tau}_{A}}{g^{e}_{A}} = 1.0019(15) \quad \frac{g^{\mu}_{V}}{g^{e}_{V}} = 0.961(61), \frac{g^{\mu}_{A}}{g^{e}_{A}} = 1.0001(13) \]
  \[ N^{\text{exp}}_{\nu} = 2.9840(82) \]
For \( \text{Re} [g_S^\tau] = 0 \) we get \( \text{Im} [g_S^\tau] = 0.59^{+0.13(+0.20)}_{-0.14(-0.29)} \)
$m_{R_2} = 0.8\text{ TeV, } m_{S_3} = 2.0\text{ TeV}$
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 ← new FF estimate QCDSR + latt [DB et al 2018]

LFV possible, eg. $\mathcal{B}(B \to K \tau \mu) < 8 \times 10^{-7}$ for $R_{\nu \nu} < 3.9$, $R_{\nu \nu}^* < 2.7$ [Belle 2017]

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

- Light LQ → impact on the shape of $pp \rightarrow \ell\ell$ distributions [Faroughy et al 2017, Greljo et al 2017]
- Recast Atlas searches for $pp \rightarrow (Z' \rightarrow)\tau\tau$ leads to bounds on $R_2$ and (weak) ones on $S_3$ for our $\theta \approx \pi/2$
- $pp \rightarrow \mu\mu$ not very useful to us, but LQ pair-production data are
  - Experimental bounds with 3.2 $fb^{-1}$ result in constraints not competitive with those obtained from LE flavor data. Projecting to 100 $fb^{-1}$ (careful with errors on bg):

![Diagram](image-url)
Direct searches (projections to $100 \text{ fb}^{-1}$)

$m_{R_2} = 0.8 \text{ TeV}, m_{S_3} = 2.0 \text{ TeV}$

- $b\bar{b}\tau\tau$ excl. (100 fb$^{-1}$)
- $\tau\tau$ excl. (100 fb$^{-1}$)
- $jj E_{\text{miss}}$ excl. (100 fb$^{-1}$)

$\text{Re}[g_3^\tau]$

$\text{Im}[g_3^\tau]$
Simple and viable $SU(5)$ GUT

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

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

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

- Available operators

\[
\begin{align*}
\mathbf{10}_i \mathbf{5}_j \mathbf{45} : & \quad y_{2 R L}^{i j} u_R^i R_2^a \varepsilon^{a b} L_L^j, b, \\
\mathbf{10}_i \mathbf{10}_j \mathbf{50} : & \quad y_{3 L L}^{i j} Q_L^c \varepsilon^{a b} (\tau^k S_3^k)_{b c} L_L^j, c
\end{align*}
\]

- 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!

- Interestingly the Yukawa couplings determined from flavor physics observables at low energy remain perturbative (below $\sqrt{4\pi}$) up to the GUT scale $\Lambda_{GUT} = 5 \times 10^{15}$ GeV, if we use 1-loop running [Wise et al 2014]
Simple and viable $SU(5)$ GUT

$m_{S_3} = 2$ TeV, $m_{R_2} = 0.8$ TeV

$|y_{GUT}| < 3$
Building a viable model which accommodates $B$-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 [$O(1 \text{ TeV})$] scalar leptoquarks. Model passes all constraints and satisfactorily accommodates $B$-physics anomalies.

$g_S$ complex, i.e. one Yukawa must be complex - e.g. $y_R^{b\tau}$

Model is of “V-A” structure in describing $b \rightarrow s\ell\ell$, but it is NOT for $b \rightarrow c\ell\bar{\nu}$.

At $\mu = m_{R2}$, effective $b \rightarrow c$ couplings satisfy $g_S = -g_P = 4g_T$

Our model is GUT inspired and allows for unification with only two LQ’s.

Yukawa couplings remain perturbative after 1-loop running to $\Lambda_{\text{GUT}}$

Results of the direct LHC searches might soon become relevant constraints too. Please do look for these LQ’s directly but PLEASE be careful with background