New physics models for the $B$-anomalies

Olcyr Sumensari

INFN and University of Padova

Implications of LHCb measurements and future prospects

CERN, October 16, 2019.
Several discrepancies $[\approx 2 - 3\sigma]$ appeared recently in $B$-meson decays:

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

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

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

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

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

This talk: (i) EFT interpretations
(ii) On the viable leptoquark models

Focus: Main predictions for LHC(b) and Belle-II
Brief overview of the $B$-anomalies
(i) \( R_{D(*)} = \frac{\mathcal{B}(B \to D(*)\tau\bar{\nu})}{\mathcal{B}(B \to D(*)\ell\bar{\nu})} \)

**Experiment** \([\approx 3.1\sigma]\)

- \( R_D \) and \( R_{D*} \): \([\approx 2\sigma]\) and \([\approx 3\sigma]\); dominated by BaBar.
- LHCb confirmed tendency \( R^{\text{exp}}_{J/\psi} > R^{\text{SM}}_{J/\psi} \), i.e. \( B_c \to J/\psi\ell\bar{\nu} \),

\( \Rightarrow \) Needs clarification from Belle-II & LHCb (run-2) data!
\( (i) \, R_{D(*)} = \mathcal{B}(B \to D(*)\tau\bar{\nu})/\mathcal{B}(B \to D(*)\ell\bar{\nu}) \)

**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?)*
\( (ii) \quad R_{K^{(*)}} = \mathcal{B}(B \to K^{(*)}\mu\mu)/\mathcal{B}(B \to K^{(*)}ee) \)

**Experiment** \([\approx 4\sigma]\)

See talk by Lisovskiyi

\[
\begin{array}{c|c}
q^2 [\text{GeV}^2] & \begin{array}{c}
R_K \\
\text{SM} \\
\text{LHCb '14} \\
\text{LHCb '19}
\end{array} \\
\hline
0 & 0.6 \pm 0.1 \\
1 & 0.8 \pm 0.1 \\
2 & 0.9 \pm 0.1 \\
3 & 1.0 \pm 0.1 \\
4 & 1.0 \pm 0.1 \\
5 & 1.0 \pm 0.1 \\
6 & 1.0 \pm 0.1 \\
\end{array}
\]

\[
\begin{array}{c|c}
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\end{array}
\]

\[\Rightarrow \text{Needs confirmation from Belle-II!}\]

**Theory** (loop induced in SM)

- Hadronic uncertainties cancel to a large extent.
  \[\Rightarrow \text{Clean observables!}\]

  [working below the narrow \( c\bar{c} \) resonances]

- QED corrections important, \( R_{K^{(*)}} = 1.00(1) \).

  [Bordone et al. '16]
EFT interpretations
What is the **scale of New Physics**?

- $R_{D(\ast)}^{\text{exp}} > R_{D(\ast)}^{\text{SM}} \Rightarrow \Lambda_{\text{NP}} \lesssim 3$ TeV  
  [perturbative couplings]

- $R_{K(\ast)}^{\text{exp}} < R_{K(\ast)}^{\text{SM}} \Rightarrow \Lambda_{\text{NP}} \lesssim 30$ TeV

see also [Di Luzio et al. 2017]
i) Effective theory for $b \rightarrow c T \bar{\nu}$

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

General messages:

- $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge invariance:
  
  $\Rightarrow g_{V_R}$ is LFU at dimension 6 ($W \bar{c}_R b_R$ vertex).
  
  $\Rightarrow$ Four coefficients left: $g_{V_L}$, $g_{S_L}$, $g_{S_R}$ and $g_T$.

- **Several viable** solutions to $R_D(*)$:
  
  - e.g. $g_{V_L} \in (0.05, 0.09)$, but **not only!**

  [Freytsis et al. 2015]

  [Angelescu, Becirevic, Faroughy, OS. 1808.08179]

  see also [Murgui et al. '19, Shi et al. '19, Blanke et al. '19]
Which Lorentz structure to pick?

$R_D \ & \ R_D^*$

Viable solutions (at $\mu \approx 1$ TeV):

$\Rightarrow g_{VL}$ and $g_{SL} = \pm 4 g_T$

See talk by Peñuelas

More exp. information is needed:

$\Rightarrow$ e.g. $B \rightarrow D^*(D\pi)\tau\bar{\nu}$

angular observables

[Becirevic et al. '19], [Murgui et al. '19]...
Which Lorentz structure to pick?

Update of [Angelescu et al. '18]

$$\chi^2_{\text{SM}} = -4 g_T \in \mathbb{R}$$

$$g_{S_L} = \pm 4 g_T \in \mathbb{R}$$

$$g_{V_L}$$

Viable solutions (at $\mu \approx 1$ TeV):

$$\Rightarrow g_{V_L} \text{ and } g_{S_L} = \pm 4 g_T$$

See talk by Peñulas

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angular observables

[Becirevic et al. '19], [Murgui et al. '19]...

Electroweak observables can also be a useful handle!

[Olcyr Sumensari (INFN and Univ. Padova)]

[Feruglio et al. '17]

[Feruglio, Paradisi, OS. '18]
From EFT to simplified models: Why leptoquarks?

Citation history:

“Leptoquarks in lepton-quark collisions”
[Buchmuller, Ruckl. ’87]
$R_{D(*)}^{\exp} > R_{D(*)}^{\text{SM}}$ require new bosons at the TeV scale:
\( R_{D(\ast)}^{\text{exp}} > R_{D(\ast)}^{\text{SM}} \) require new bosons at the TeV scale:

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]
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In summary: See talks by Peñuelas and Soni

- Charged Higgs solutions are in tension with $\tau_{Bc}$ constraint [Alonso et al. '16]
- Minimal $W'$ models: tension with high-$p_T$ constraints
- Scalar and vector leptquarks (LQ) are the best candidates so far.
Which LQ for $R_{D(*)}$?

<table>
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<th>$g_{eff}^{b\rightarrow c\tau\nu}(\mu = m_\Delta)$</th>
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<td>✓</td>
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<tr>
<td>$R_2 = (3, 2, 7/6)$</td>
<td>$g_{S_L} = 4 , g_T$</td>
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Viable models: [Angelescu, Becirevic, Faroughy, OS. 1808.08179]

- $U_1$ ($g_{V_L}$), $S_1$ ($g_{V_L}$ and $g_{S_L} = -4 \, g_T$), and $R_2$ ($g_{S_L} = 4 \, g_T \in \mathbb{C}$)
- Possibility to distinguish them by using other $b \rightarrow c\ell\nu$ observables!
ii) Effective theory for $b \rightarrow s \ell \ell$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[ C_9(\mu) \langle \bar{s} \gamma_\mu P_L b \rangle \langle \bar{\ell} \gamma^\mu \ell \rangle + C_{10}(\mu) \langle \bar{s} \gamma_\mu P_L b \rangle \langle \bar{\ell} \gamma^\mu \gamma^5 \ell \rangle \right] + \ldots$$

Fit to **clean quantities**: $B(B_s \rightarrow \mu\mu)$ and $R_K(*)$.

- Only vector (axial) coefficients can accommodate data.
- $C_9 = -C_{10}$ allowed – **predicted** by left-handed operator!

Interesting: Conclusion **corroborated by global $b \rightarrow s \ell \ell$ fit!**

cf. e.g. [Capdevilla et al. '19], [Aebischer et al. '19], [Arbey et al.]...
Which LQs for $R_{D(*)}$ and $R_{K(*)}$?

[Angelescu, Becirevic, Faroughy, OS. 1808.08179]

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

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  ⇒ Viable TeV models proposed (with more than one mediator!)

[Di Luzio et al. ’17, Bordone et al. ’17, Assad et al. ’17, Blanke et al. ’17…].
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  ⇒ Viable TeV models proposed (with more than one mediator!)
    [Di Luzio et al. '17, Bordone et al. '17, Assad et al. '17, Blanke et al. '17…].

- Two scalar LQs are also viable:
  ⇒ $S_1$ and $S_3$ [Crivellin et al. '17, Marzocca. '18], $R_2$ and $S_3$ [Becirevic et al. '18].
UV completion:  \( U_1 = (3, 1, 2/3) \)

Pati-salam unification:

\[ \mathcal{G}_{PS} = SU(4) \times SU(2)_L \times SU(2)_R \] contains \( U_1 \) as gauge boson.

• Main difficulty: flavor universal \( \Rightarrow m_{U_1} \gtrsim 100 \text{ TeV} \) from FCNC.
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\[ \text{Viable scenario for B-anomalies:} \]

- \( SU(4) \times SU(3)' \times SU(2)_L \times U(1)' \rightarrow G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y \)
- Flavor violation from (ad-hoc) mixing with vector-like fermions.
- **Main feature**: \( U_1 + Z' + g' \) at the TeV scale.

Rich LHC pheno, cf. [Baker et al. '19], [Di Luzio et al. '18]
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Viable scenario for \( B \)-anomalies: 

- \( SU(4) \times SU(3)' \times SU(2)_L \times U(1)' \) \( \rightarrow \) \( G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y \)
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- Main feature: \( U_1 + Z' + g' \) at the TeV scale.
  Rich LHC pheno, cf. [Baker et al. '19], [Di Luzio et al. '18]

Step beyond: \( [PS]^3 = [SU(4) \times SU(2)_L \times SU(2)_R]^3 \) 

- Hierarchical LQ couplings fixed by symmetry breaking pattern.
- Explanation of fermion masses and mixing (flavor puzzle)!

Olcyr Sumensari (INFN and Univ. Padova)
Two scalar leptoquarks

- Prefer scalar to vector LQ to remain minimalistic in terms of new parameters and to be able to compute loops.
Two scalar leptoquarks

- Prefer scalar to vector LQ to remain *minimalistic* in terms of new parameters and to be able to compute loops.

- In flavor basis

\[
\mathcal{L} \supset y^i_R \, \bar{Q}_i \ell_R \, R_2 + y^i_L \, \bar{u}_{R_i} \, L_j \, \tilde{R}^i_2 + y^i \, \bar{Q}_i^C \, i\tau_2 (\tau_k \, S^k_3) \, L_j + \text{h.c.}
\]

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

and assume \( y_R = y^T_R \) and \( y = -y_L \) (GUT aspirations).

- \( SU(5) \) embedding is possible with these two light scalar LQs.
Two scalar leptoquarks

- Prefer scalar to vector LQ to remain **minimalistic** in terms of new parameters and to be able to compute loops.

- In flavor basis

  \[ \mathcal{L} \supset y_{R}^{ij} \bar{Q}_i \ell_{Rj} R_2 + y_{L}^{ij} \bar{u}_{Ri} L_j \tilde{R}_2^\dagger + y^{ij} \tilde{Q}_i^C i \tau_2 (\tau_k S^k_3) L_j + \text{h.c.} \]

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- **SU(5)** embedding is possible with these two light scalar LQs.

- Data can be fully described by **few parameters**:

  \[ \Rightarrow 2 \text{ masses, 3 couplings and 1 angle.} \]

  \[ \Rightarrow V - A \text{ structure for } b \rightarrow s \ell \ell, \text{ but NOT for } b \rightarrow c \tau \bar{\nu} \text{ (scalar/tensor).} \]

  (see back-up for details)
LHC constraints

- LQ pair-production via QCD:

  \[ S_3 = (\bar{3}, 3, 1/3) \]

  \[ m_{S_3} \gtrsim 1.4 \text{ TeV} \]

  \[ \text{assuming } B(S_3 \rightarrow b\mu) \approx 1 \]

- Di-lepton tails at high-pT:

  \[ \text{See talk by Soni} \]

\[ \text{[CMS-PAS-EXO-17-003]} \]

\[ \text{[ATLAS. 1707.02424, 1709.07242]} \]

\[ \text{[Angelescu, Becirevic, Faroughy, OS. '18]} \]

\[ \text{[Faroughy et al. '15]} \]

\[ \text{See talk by Soni} \]
Results and predictions:

\[ g_{SL} = 4 \, g_T \]

\[ m_{R_2} = 0.8 \, \text{TeV}, \, m_{S_3} = 2.0 \, \text{TeV} \]
Direct searches (projections to $100 \text{ fb}^{-1}$)

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

$pp \rightarrow \tau \nu$

Grejko et al. '18

$\tau \tau \text{ excl. (100 fb}^{-1})$

$ij \ E_{\text{miss}} \text{ excl.(100 fb}^{-1})$

$R_D^*$

$R_D$
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: $\mathcal{B}(B \to K\mu\tau) \gtrsim 2 \times 10^{-7}$
- BaBar: $\mathcal{B}(B \to K\mu\tau) < 4.8 \times 10^{-5}$ (90% CL.). Can we do better?
Large effects in $b \rightarrow s \mu \tau$ are a common prediction of minimal solutions to the $B$-anomalies:

see also [Guadagnoli et al. '14]

$\Rightarrow$ LHCb [NEW '19]: $\mathcal{B}(B_s \rightarrow \mu \tau) < 4.2 \times 10^{-5}$. 
Large effects in $b \to s \mu \tau$ are a common prediction of minimal solutions to the $B$-anomalies: see also [Guadagnoli et al. '14]

⇒ LHCb [NEW '19]: $\mathcal{B}(B_s \to \mu \tau) < 4.2 \times 10^{-5}$.

i) If purely $(V - A) \times (V - A)$:

$$\frac{\mathcal{B}(B_s \to \mu \tau)}{\mathcal{B}(B \to K \mu \tau)} \approx 0.8, \quad \frac{\mathcal{B}(B \to K^* \mu \tau)}{\mathcal{B}(B \to K \mu \tau)} \approx 1.8$$

ii) If scalar operators are present:

$$\frac{\mathcal{B}(B_s \to \mu \tau)}{\mathcal{B}(B \to K^{(*)} \mu \tau)} \gg 1$$

[Becirevic, OS, Zukanovich. '16]
Last but not least...

\[ S_1 & S_3 \]

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<td>✓</td>
<td>☒</td>
</tr>
<tr>
<td>$U_1 = (3, 1, 2/3)$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$U_3 = (3, 3, 2/3)$</td>
<td>☒</td>
<td>✓</td>
<td>☒</td>
</tr>
</tbody>
</table>

Good candidate to also explain $(g - 2)_\mu$? [Dorsner, Fajfer, OS. '19]
Summary and perspectives

◦ Flavor anomalies are still there, but the experimental situation after Moriond ’19 is (perhaps) less convincing.

   Needs clarification from LHCb and Belle-II!

◦ We identify/summarize the viable single-mediator scenarios to explain $R_{K^*(\ast)}$ and/or $R_{D^*(\ast)}$.

   Only the vector $U_1$ is viable. Two scalar LQs can do the job too.

◦ There is a pronounced complementarity of flavor physics constraints with those obtained from the direct searches at the LHC.

   Minimal scenarios $\Rightarrow$ lower bound $\mathcal{B}(B \to K\mu\tau) \gtrsim \mathcal{O}(10^{-7})$

◦ Building a concrete model to simultaneously explain $R_{K^*(\ast)}$ and $R_{D^*(\ast)}$ remains challenging.

   Data-driven model building!
Thank you!
Back-up
• **3.1σ 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)!
\[
\frac{R_{D(*)}}{R_{SM}^{D(*)}} = 1 + a_S^{D(*)} |g_S^\tau|^2 + a_P^{D(*)} |g_P^\tau|^2 + a_T^{D(*)} |g_T^\tau|^2 \\
+ a_{SV_L}^{D(*)} \text{Re} [g_S^\tau] + a_{PV_L}^{D(*)} \text{Re} [g_P^\tau] + a_{TV_L}^{D(*)} \text{Re} [g_T^\tau],
\]

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>(a_M^S)</th>
<th>(a_{SV_L}^M)</th>
<th>(a_M^P)</th>
<th>(a_{PV_L}^M)</th>
<th>(a_M^T)</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>
\( R_2 = (3, 2, 7/6), \ S_3 = (\bar{3}, 3, 1/3) \)

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

and assume

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

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

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

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

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

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

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

\[\Rightarrow\] Phenomenology suggests $\theta \approx \pi/2$ and $y_R^{b\tau}$ complex
Notable flavor constraints...

- $R_{e/\mu}^K \exp = 2.488(10) \times 10^{-5}$ [PDG], $R_{e/\mu}^K \SM = 2.477(1) \times 10^{-5}$ [Cirigliano. '07]

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

- $R_{\mu/e}^D \exp = 0.995(45)$ [Belle. '17], $R_{\mu/e}^D \exp = 1.04(5)$ [Belle. '16]

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

- $\mathcal{B}(\tau \to \mu\phi) < 8.4 \times 10^{-8}$ [Belle.'11], loops: $\mathcal{B}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$ [BaBar. '10]

- Loops: $\Delta m_{B_s} \exp = 17.76(2) \text{ ps}^{-1}$ [PDG], $\Delta m_{B_s} \SM = (20.1^{+1.2}_{-1.6}) \text{ ps}^{-1}$ [FLAG '19]

- Loops: $Z \to \mu\mu$, $Z \to \tau\tau$, $Z \to \nu\bar{\nu}$ [LEP] see also [Arnan, Becirevic, Mescia, OS. '19]

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

  $$N_\nu \exp = 2.9840(82)$$

$R_2 \& S_3 \text{ GUT}$
\[ 16\pi^2 \frac{d \log y^b_L}{d \log \mu} = |y^c_L|^2 + |y^c_R|^2 + \frac{9}{2} |y^b_L|^2 + \frac{y_t^2}{2} + \ldots \]

\[ m_{R_2} = 0.8 \text{ TeV}, m_{S_3} = 2.0 \text{ TeV}, |\theta| \approx \pi/2 \]

\[ y^b_L = e^{i \pi \setminus 180^\circ} |y^b_L| \]

\[ |y_{\text{GUT}}| < \sqrt{4\pi} \]

\[ \Rightarrow \text{Yukawas remain perturbative after 1-loop running to } \Lambda_{\text{GUT}}! \]
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. ’17]

- Available operators

\[
10_i 5_j 45 : \quad y_{2,ij}^{RL} \bar{u}^i_R \epsilon^{ab} R_2^a L^j, b, \quad y_{3,ij}^{LL} \bar{Q}^i, a \epsilon^{ab} (\tau^k S^k_3)^{bc} L^j, c
\]

\[
10_i 10_j 50 : \quad y_{2,ij}^{LR} \bar{e}^i_R \epsilon^{ab} R_2^a Q^j, a
\]

- 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]
\[ R_2 = (3, 2, 7/6) \]

\[ \mathcal{L}_{R_2} = y_{ij}^R \bar{Q}_i \ell_{Rj} R_2 - y_{ij}^L \bar{u}_{Ri} R_2 i \tau_2 L_j + \text{h.c.} \]

\[ C_{kl}^{\text{tree}} = C_{10}^{\text{tree}} = -\frac{\pi v^2}{2 V_{tb} V_{ts}^* \alpha_{\text{em}}} \frac{y_R^{sl}(y_R^{bk})^*}{m_{R_2}^2}. \]

\[ C_{kl}^{\text{loop}} = -C_{10}^{\text{loop}} = \sum_{u, u' \in \{u, c, t\}} \frac{V_{ub} V_{u's}^*}{V_{tb} V_{ts}^*} y_L^{u'l} (y_L^{u'l})^* \mathcal{F}(x_u, x_{u'}) \]

\[ y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & 0 \\ 0 & y_L^{i\mu} & 0 \end{pmatrix}, \quad y_R = 0 \]

\[ y_L^{c\mu} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & 0 \\ 0 & y_L^{i\mu} & 0 \end{pmatrix} \]

\[ s \quad u' \quad \ell_1 \]

\[ b \quad u \quad \ell_1 \]

\[ W \quad R_2^{(5/3)} \]

\[ s \quad u' \quad \ell_2 \]

\[ R_K \approx R_{K^*} \]

\[ m_{R_2} = 1.5 \text{ TeV} \]

\[ \text{LHC bounds } pp \to \mu \nu \]

\[ \text{LEP bounds } Z \to \mu \mu \]

Update of [Becirevic, OS. ’17]
### Limits on LQ pair-production

[Angelescu, Becirevic, Faroughy, OS. 1808.08179]

<table>
<thead>
<tr>
<th>Decays</th>
<th>LQs</th>
<th>Scalar LQ limits</th>
<th>Vector LQ limits</th>
<th>$\mathcal{L}_{\text{int}}$ / Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$jj\tau\bar{\tau}$</td>
<td>$S_1, R_2, S_3, U_1, U_3$</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$b\bar{b}\tau\bar{\tau}$</td>
<td>$R_2, S_3, U_1, U_3$</td>
<td>850 (550) GeV</td>
<td>1550 (1290) GeV</td>
<td>12.9 fb$^{-1}$ [49]</td>
</tr>
<tr>
<td>$t\bar{t}\tau\bar{\tau}$</td>
<td>$S_1, R_2, S_3, U_3$</td>
<td>900 (560) GeV</td>
<td>1440 (1220) GeV</td>
<td>35.9 fb$^{-1}$ [50]</td>
</tr>
<tr>
<td>$jj\mu\bar{\mu}$</td>
<td>$S_1, R_2, S_3, U_1, U_3$</td>
<td>1530 (1275) GeV</td>
<td>2110 (1860) GeV</td>
<td>35.9 fb$^{-1}$ [51]</td>
</tr>
<tr>
<td>$b\bar{b}\mu\bar{\mu}$</td>
<td>$R_2, U_1, U_3$</td>
<td>1400 (1160) GeV</td>
<td>1900 (1700) GeV</td>
<td>36.1 fb$^{-1}$ [52]</td>
</tr>
<tr>
<td>$t\bar{t}\mu\bar{\mu}$</td>
<td>$S_1, R_2, S_3, U_3$</td>
<td>1420 (950) GeV</td>
<td>1780 (1560) GeV</td>
<td>36.1 fb$^{-1}$ [53, 54]</td>
</tr>
<tr>
<td>$jj\nu\bar{\nu}$</td>
<td>$R_2, S_3, U_1, U_3$</td>
<td>980 (640) GeV</td>
<td>1790 (1500) GeV</td>
<td>35.9 fb$^{-1}$ [55]</td>
</tr>
<tr>
<td>$b\bar{b}\nu\bar{\nu}$</td>
<td>$S_1, R_2, S_3, U_3$</td>
<td>1100 (800) GeV</td>
<td>1810 (1540) GeV</td>
<td>35.9 fb$^{-1}$ [55]</td>
</tr>
<tr>
<td>$t\bar{t}\nu\bar{\nu}$</td>
<td>$R_2, S_3, U_1, U_3$</td>
<td>1020 (820) GeV</td>
<td>1780 (1530) GeV</td>
<td>35.9 fb$^{-1}$ [55]</td>
</tr>
</tbody>
</table>