B-physics anomalies: a road to new physics?

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hep-ph/1808.08179

In collaboration with

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MPIK Heildeberg, June 15, 2020

University of Zurich[UZH]

European Research Council

Established by the European Commission

Outline

i) Introduction

ii) Overview of the B-physics anomalies

iii) EFT interpretations

iv) From EFT to concrete models

v) Closing the leptoquark window

Introduction

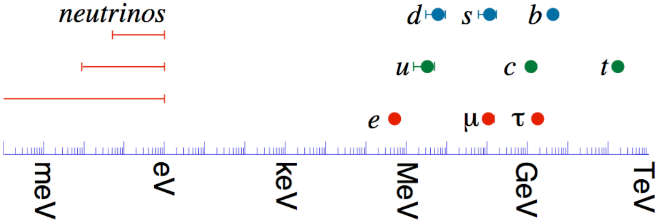
- Gauge sector of the SM entirely **fixed by symmetry**:
  - ⇒ Only a handful of parameters.
  - ⇒ Theory renormalizable and verified at the loop level (oblique parameters).
- Flavor sector **loose**:
  - ⇒ 13 free parameters (masses and quark mixing) – fixed by data.

$$\mathcal{L}_Y = -Y_\ell\, \bar{L}\, \Phi\, \ell_R - Y_d\, \bar{Q}\, \Phi\, d_R - Y_u\, \bar{Q}\, \tilde{\Phi}\, u_R + \text{h.c.}$$

  - ⇒ These (many) parameters exhibit a hierarchical structure which we do not understand.

Origin of flavor?

- Striking hierarchy *[does not look accidental. . .]* ⇒ Flavor theory?
- Why three families? Why do *quarks* and *leptons* mix in *different ways*?

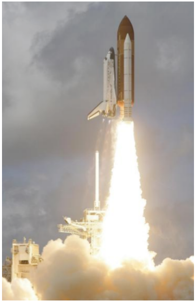


"Who ordered that?"

To identify (broken) symmetries beyond those present in the SM is one of the roles of flavor physics

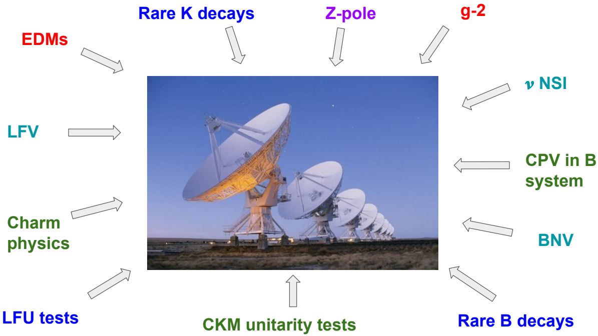
Indirect searches of New Physics

LHC at high-p_T



Unique effort toward the energy frontier

Flavor physics



Collective effort

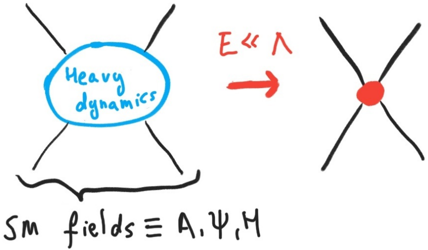
Indirect searches are complementary to the direct searches at the LHC and can probe energy scales that are not directly accessible at colliders

How do we do it?

The SM is an effective theory at low energies limit of a more fundamental theory which is still unknown:

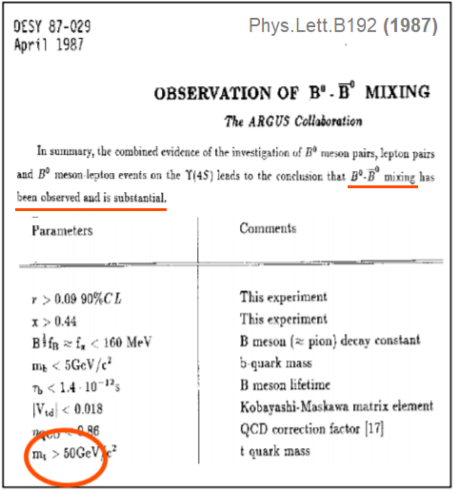
$$\mathcal{L}_{\text{eff}} = \overbrace{\mathcal{L}_{\text{gauge}}(A,\Psi) + \mathcal{L}_{\text{Higgs}}(A,\Psi,H)}^{\mathcal{L}_{\text{SM}}\ \text{(renormalizable)}} + \underbrace{\sum_{d\geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}_n^{(d)}(A,\Psi,H)}_{\text{Operators of dim} \geq 5 \text{ made of SM fields}},$$

This is the most general description of new heavy degrees of freedom as long as there is not enough energy to produce them



Why should I care?

An example: B^0-$\overline{B^0}$ oscillation


DESY 87-029
April 1987

Phys.Lett.B192 **(1987)**

OBSERVATION OF B^0-$\overline{B}^0$ MIXING

The ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson-lepton events on the $\Upsilon(4S)$ leads to the conclusion that B^0-$\bar{B}^0$ mixing has been observed and is substantial.

Parameters	Comments
$r > 0.09$ 90%CL	This experiment
$x > 0.44$	This experiment
$B^{\frac{1}{2}} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$ pion) decay constant
$m_b < 5\text{GeV}/c^2$	b-quark mass
$\tau_b < 1.4 \cdot 10^{-12}$s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi-Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [17]
$m_t > 50\text{GeV}/c^2$	t quark mass

GIM mechanism:

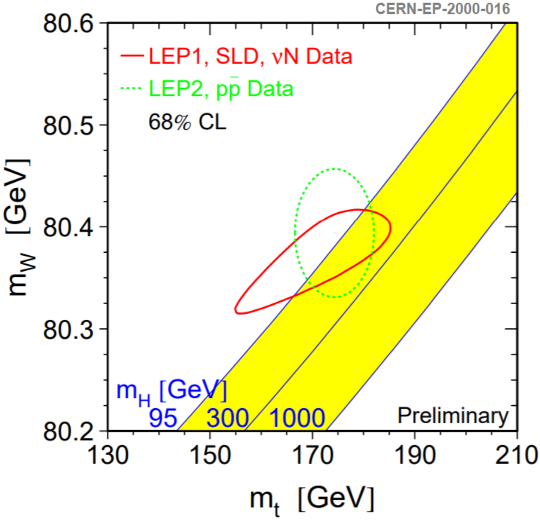
$$\mathcal{M}(B^0 - \overline{B^0}) \propto \sum_{ij} V_{ib}^* V_{id} V_{jb}^* V_{jd} \mathcal{F}(m_{u_i}^2, m_{u_j}^2)$$

[Grossman, Tanedo. TASI Lectures, '17]

The unbelievably heavy top quark. Carlos Wagner once wrote a paper in the 80s that assumed the top mass to be around 50 GeV, for which it was promptly rejected by the journal editor as being unreasonably heavy. When you put the 50 GeV top into the above calculation you predict that B mixing is very small. In the early 80s, flavor physicists found that B mixing is, in fact, order one. The natural explanation was that the top was heavy, and indeed, flavor measurements in 1981 suggested $m_t \sim 150$ GeV. People didn't believe this because it was so ridiculously large. It wasn't until much later that electroweak precision tests predicted the same value. Historically people often say that electroweak precision experiments predicted a heavy top, but it was in fact B–$\bar{B}$ mixing that was the *first* avatar of a heavy top—we just weren't ready to believe it!

Top-quark discovery

The top-quark discovery was a combined effort of precision physics (LEP) with seaches at high-energies (Tevatron).



Brief overview of the B-anomalies

Motivation

Several discrepancies appeared recently in B-meson decays:

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

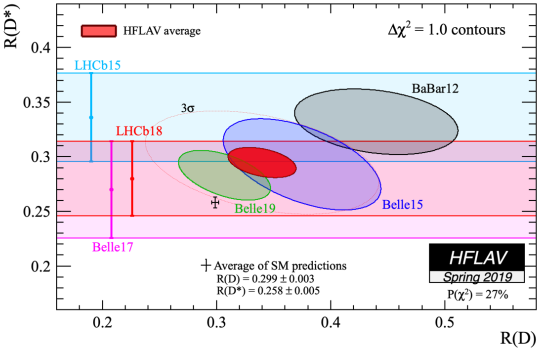
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}\Bigg|_{q^2\in[q^2_{\mathrm{min}},q^2_{\mathrm{max}}]} \qquad \& \qquad R_{K^{(*)}}^{\mathrm{exp}} < R_{K^{(*)}}^{\mathrm{SM}}$$

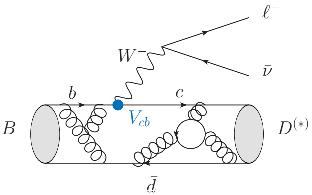
$\Rightarrow$ Violation of **L**epton **F**lavor **U**niversality (LFU)?

NB. LFU broken in the SM by Yukawas. Well tested property only for first generations.

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

Experiment $[\approx 3.1\sigma]$





- R_D and R_{D^*}: $[\approx 2\sigma]$ and $[\approx 3\sigma]$; dominated by BaBar.
- LHCb confirmed tendency $R_{J/\psi}^{\text{exp}} > R_{J/\psi}^{\text{SM}}$, 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 $q^2 \neq q^2_{\max}$ $(w > 1)$ available for both leading (vector) and subleading (scalar) form factors [MILC 2015, HPQCD 2015]

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

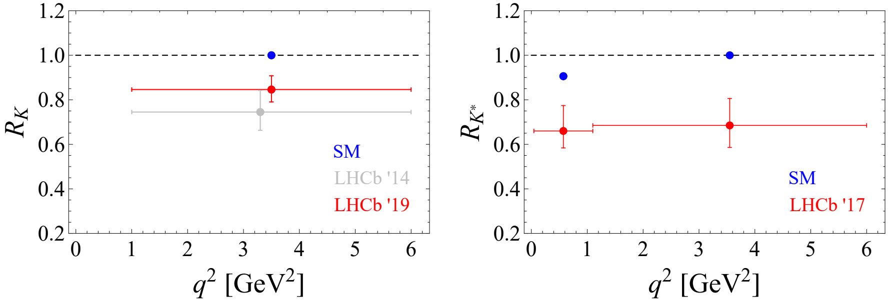
with $f_+(0) = f_0(0)$.

- R_{D^*}: lattice QCD at $q^2 \neq q^2_{\max}$ 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?) **[Preliminary LQCD results by Fermilab/MILC!]**

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

Experiment $[\approx 4\sigma]$ (see R_{pK} in back-up)



$\Rightarrow$ **Needs confirmation from Belle-II!**

Theory (loop induced in SM) [Kruger, Hiller. '03]

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

Relevant questions:

- Is there a **model of New Physics** to explain these anomalies?
- Which additional **experimental signatures** should we expect?

Data-driven approach:

Data ⟹ EFT ⟹ Simplified model ⟹ UV completion

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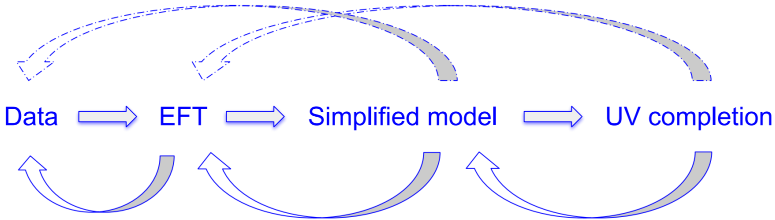
Data-driven approach:



EFT interpretations

[Angelescu, Becirevic, Faroughy, **OS**. '18]

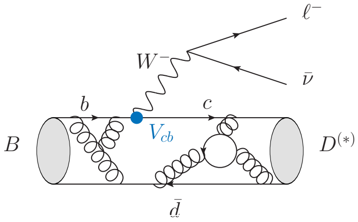
[Feruglio, Paradisi, **OS**. '18]

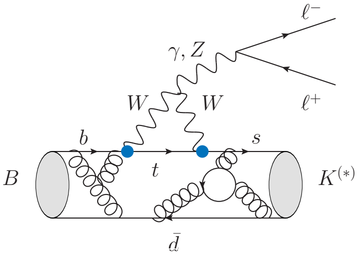
...

What is the **scale of New Physics**? see e.g. [Di Luzio et al. '17]

- $R_{D^{(*)}}^{\mathrm{exp}} > R_{D^{(*)}}^{\mathrm{SM}} \quad \Rightarrow \quad \Lambda_{\mathrm{NP}} \lesssim 3$ TeV
- $R_{K^{(*)}}^{\mathrm{exp}} < R_{K^{(*)}}^{\mathrm{SM}} \quad \Rightarrow \quad \Lambda_{\mathrm{NP}} \lesssim 40$ TeV

(assuming perturbative couplings)





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

R_D & R_{D^*}

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

General messages:

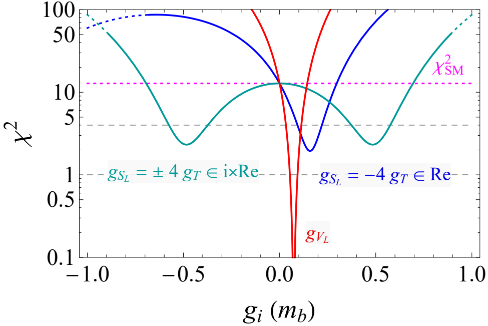
- $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge invariance:
  $\Rightarrow$ g_{V_R} is LFU at dimension 6 ($W \bar{c}_R b_R$ vertex).
  $\Rightarrow$ Four coefficients left: g_{V_L}, g_{S_L}, g_{S_R} and g_T.

- Several viable solutions to $R_{D^{(*)}}$: [Freytsis et al. 2015]
  - e.g. $g_{V_L} \in (0.05, 0.09)$, but not only!

[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?

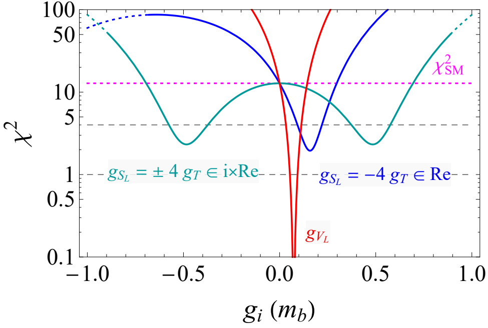


Viable solutions (at $\mu \approx 1$ TeV):

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

Which Lorentz structure to pick?

Update of [Angelescu et al. '18]



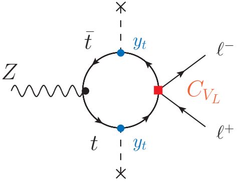
Viable solutions (at $\mu \approx 1$ TeV):

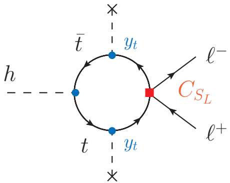
$\Rightarrow$ g_{V_L} and $g_{S_L} = \pm 4\, g_T$

More exp. information is needed:

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

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





Electroweak observables can also be a useful handle!

[Feruglio et al. '17]

[Feruglio, Paradisi, **OS**. '18]

From EFT to concrete models

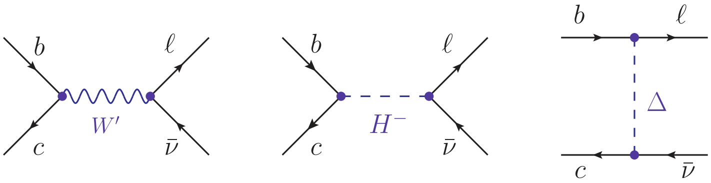
[Becirevic, **OS**. '17]

[Angelescu, Becirevic, Faroughy, **OS**. '18]

[Becirevic, Dorsner, Fajfer, Faroughy, Kosnik, **OS**. '18]

. . .

$R_{D^{(*)}}^{\mathrm{exp}} > R_{D^{(*)}}^{\mathrm{SM}}$ require new bosons at the TeV scale:



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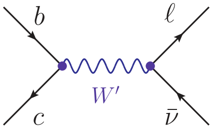

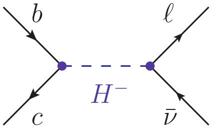

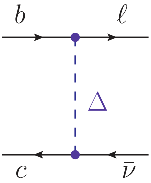

Challenges for New Physics:

- Loop constraints: e.g. $\tau \to \mu\nu\bar{\nu}$, $Z \to \ell\ell$ [Feruglio et al., '16]
- LHC direct and indirect bounds [Greljo et al. '15, Faroughy et al., '16]

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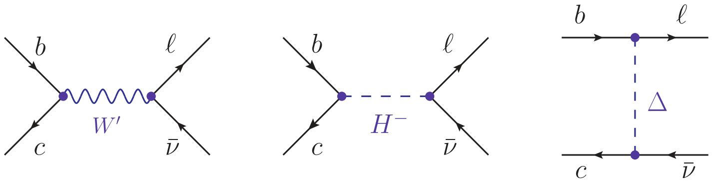

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In Summary:

- Minimal W' models: tension with high-p_T ditau constraints
- Charged Higgs solutions are in tension with τ_{B_c} constraint [Alonso et al. '16]
- Scalar and vector **leptoquarks (LQ)** are the **best candidates** so far.

Which LQ for $R_{D^{(*)}}$?

NB. w/o ν_R

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}	✗
...	...	...

[Angelescu, Becirevic, Faroughy, **OS**. '18]

ii) Effective theory for $b \to s\ell\ell$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + \sum_{i=7,8,9,10,P,S,\dots} \Big(C_i(\mu)\mathcal{O}_i + C_i'(\mu)\mathcal{O}_i' \Big) \right]$$

- Operators relevant to $b \to s\ell\ell$ are

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma^5 \ell)$$

$$\mathcal{O}_S^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\ell) \qquad \mathcal{O}_P^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell)$$

$$\mathcal{O}_7^{(\prime)} = m_b(\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$

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- Dimension-6 tensor operators are not allowed by $SU(2)_L \times U(1)_Y$.

[Buchmuler, Wyler. '85]

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- Dimension-6 tensor operators are not allowed by $SU(2)_L \times U(1)_Y$.

[Buchmuler, Wyler. '85]

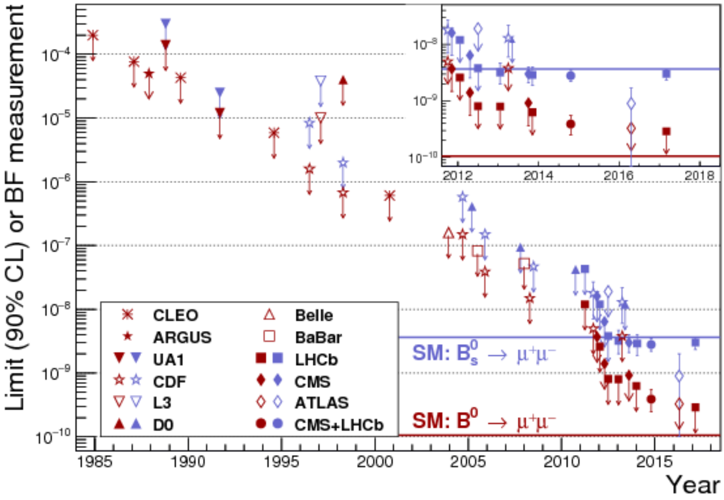
- (Pseudo)scalar operators are tightly constrained by

$\overline{\mathcal{B}}(B_s \to \mu\mu)^{\text{exp}} = (2.9 \pm 0.5) \times 10^{-9}$ [LHCb, '17], [CMS, Atlas. '18]

$\overline{\mathcal{B}}(B_s \to \mu\mu)^{\text{SM}} = (3.67 \pm 0.16) \times 10^{-9}$ [De Bruyn et al. '12], [Bobeth et al. '13] [Beneke et al. '19]

A long journey...

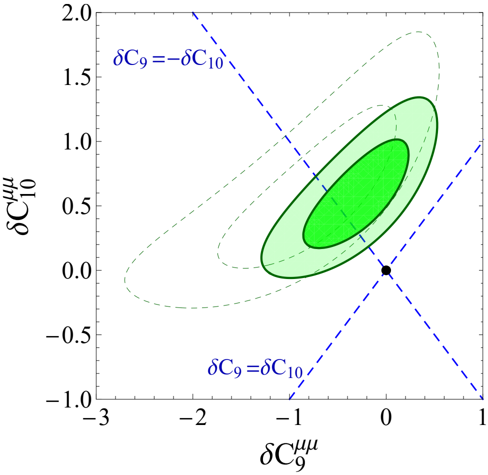
[LHCb-PAPER-2014-049]



To be improved at LHC(b) and Belle-II!

Fit to clean quantities: $\mathcal{B}(B_s \to \mu\mu)$ and $R_{K^{(*)}}$

EFT for $b \to s\ell\ell$



- Only vector (axial) coefficients can accommodate data.
- $C'_{9,10}$ disfavored by $R_{K^*}^{\text{exp}} < R_{K^*}^{\text{SM}}$.
- $C_9 = -C_{10}$ allowed – consistent with a left-handed $SU(2)_L$ invariant operator!

see e.g. [Becirevic, **OS**. '16]

Interesting: Conclusion corroborated by global $b \to s\ell\ell$ fit.

cf. e.g. [Aebischer et al. '19], [Arbey et al. '19], [Capdevilla et al. '19]...

Which LQs for $R_{D^{(*)}}$ and $R_{K^{(*)}}$?

[Angelescu, Becirevic, Faroughy, **OS**. '18]

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

- Only U_1 can do the job, but UV completion needed.

  $\Rightarrow \mathcal{G}_{\text{PS}} = SU(4) \times SU(2)_L \times SU(2)_R$ contains $U_1 = (3, 1, 2/3)$

  $\Rightarrow$ Viable $\mathcal{O}(\text{TeV})$ models proposed: $U_1 + Z' + g'$ (more than one mediator!)

  [Di Luzio et al. '17]

- Two scalar LQs are a legitimate option:

  $\Rightarrow S_1$ & S_3 [Crivellin et al. '17, Marzocca. '18]

  $\Rightarrow R_2$ & S_3 from $SU(5)$ GUT [Becirevic et al. **OS**. '18].

UV completion: $U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$

Pati-salam unification: [Pati, Salam. '74]

- $\mathcal{G}_{\rm PS} = SU(4) \times SU(2)_L \times SU(2)_R$ contains U_1 as gauge boson.
- Main difficulty: flavor universal $\Rightarrow$ $m_{U_1} \gtrsim 100$ TeV from FCNC.

Viable scenario for B-anomalies: [Di Luzio et al. '17]

- $SU(4) \times SU(3)' \times SU(2)_L \times U(1)' \to \mathcal{G}_{\rm SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$
- 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]

Step beyond: $[\mathrm{PS}]^3 = [SU(4) \times SU(2)_L \times SU(2)_R]^3$ [Bordone et al. '17]

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

Closing the leptoquark window:

$$U_1 = (3, 1, 2/3)$$

[Angelescu, Becirevic, Faroughy, **OS**. 1808.08179]

Example: $U_1 = (3, 1, 2/3)$

[Angelescu, Becirevic, Faroughy, **OS**. '18]

$$\mathcal{L} = x_L^{ij}\, \bar{Q}_i \gamma_\mu U_1^\mu L_j + x_R^{ij}\, \bar{d}_{Ri} \gamma_\mu U_1^\mu \ell_{Rj} + \text{h.c.}\,,$$

- $b \to c\tau\bar{\nu}$:

$$\mathcal{L}_{\text{eff}} \supset -\frac{\left(x_L^{b\tau}\right)^* \left(V x_L\right)^{c\tau}}{m_{U_1}^2} (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L)$$

- $b \to s\mu\mu$:

$$\mathcal{L}_{\text{eff}} \supset -\frac{\left(x_L\right)^{s\mu} \left(x_L^{b\mu}\right)^*}{m_{U_1}^2} (\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L)$$

$$x_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix}$$

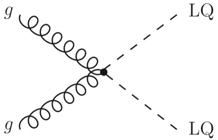
- Other observables: $\tau \to \mu\phi$, $B \to \tau\bar{\nu}$, $D_{(s)} \to \mu\bar{\nu}$, $D_s \to \tau\bar{\nu}$, $K \to \mu\bar{\nu}/K \to e\bar{\nu}$, $\tau \to K\bar{\nu}$ and $B \to D^{(*)}\mu\bar{\nu}/B \to D^{(*)}e\bar{\nu}$.

LHC constraints

$U_1 = (3, 1, 2/3)$

- LQ pair-production via QCD:

[CMS-PAS-EXO-17-003]

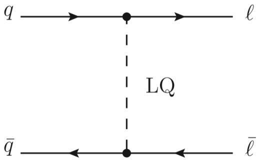


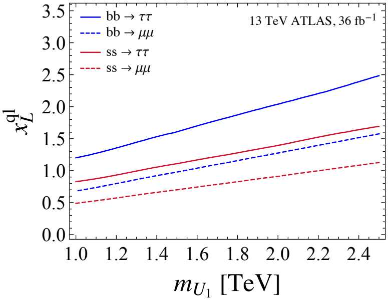
$$m_{U_1} \gtrsim 1.5 \text{ TeV}$$

[*assuming* $\mathcal{B}(U_1 \to b\tau) \approx 0.5$]

- Di-lepton tails at high-pT:

[ATLAS. 1707.02424,1709.07242]

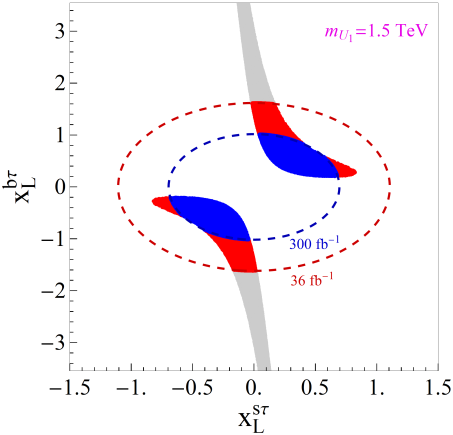




[Angelescu, Becirevic, Faroughy, **OS**. '18]

[see also Faroughy et al. '15]

Combining low and high-energy constraints $U_1 = (3, 2, 1/3)$



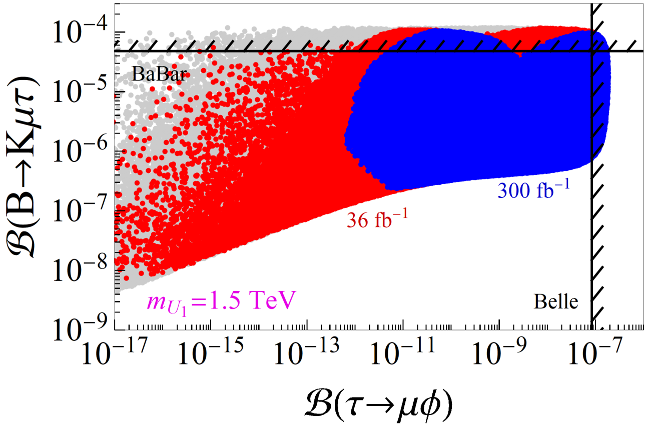
$R_{D^{(*)}}$ depends on:

$$g_{V_L} = \frac{v^2}{2m_{U_1}^2}\left(x_L^{b\tau}\right)^*\left(x_L^{b\tau} + \frac{V_{cs}}{V_{cb}} x_L^{s\tau}\right)$$

Same couplings probed by $\underline{pp \to \tau\tau}$:
36 fb^{-1} (blue) and 300 fb^{-1} (red).

⇒ Upper limit on $|x_L^{b\tau}|$ implies a nonzero lower limit on $|x_L^{s\tau}|$!

- Combination of flavor and high-p_T sets upper and **lower bounds** on **LFV** rates: $\mathcal{B}(B \to K\mu\tau) \gtrsim \text{few} \times 10^{-7}$

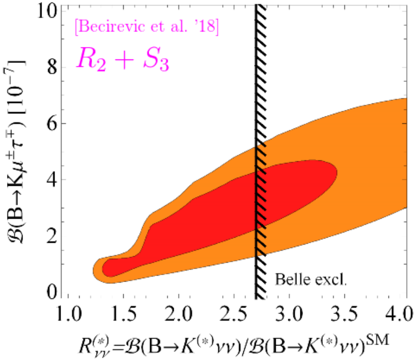


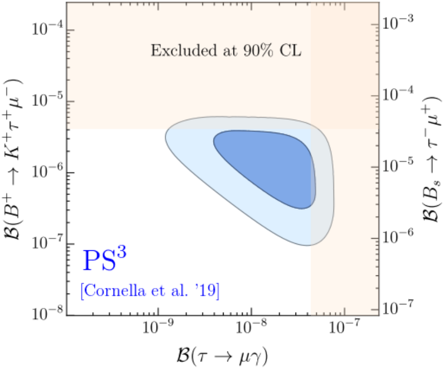
- BaBar: $\mathcal{B}(B \to K\mu\tau) < 4.8 \times 10^{-5}$. Can we do better?

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

Large effects in $b \to s\mu\tau$ are a common prediction of minimal solutions to the B-anomalies:

see also [Glashow et al. '14]





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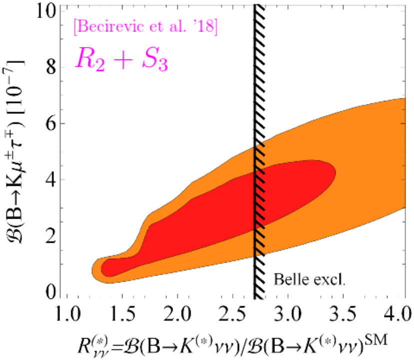
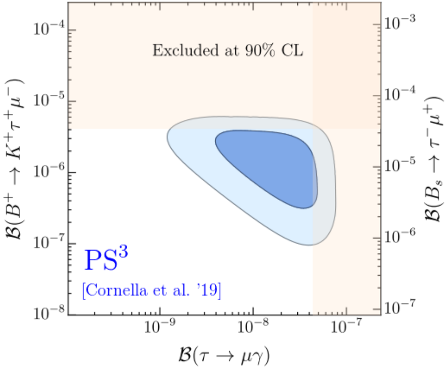




i) If purely $(V-A)\times(V-A)$:

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

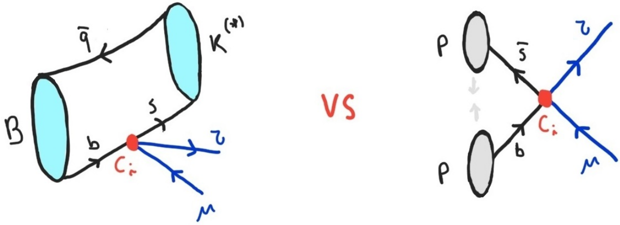
ii) If scalar operators are present:

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

[Becirevic, **OS**, Zukanovich. '16]

LFV and high-p_T tails

[Angelescu, Faroughy, **OS**. '20]



LFV and high-p_T tails

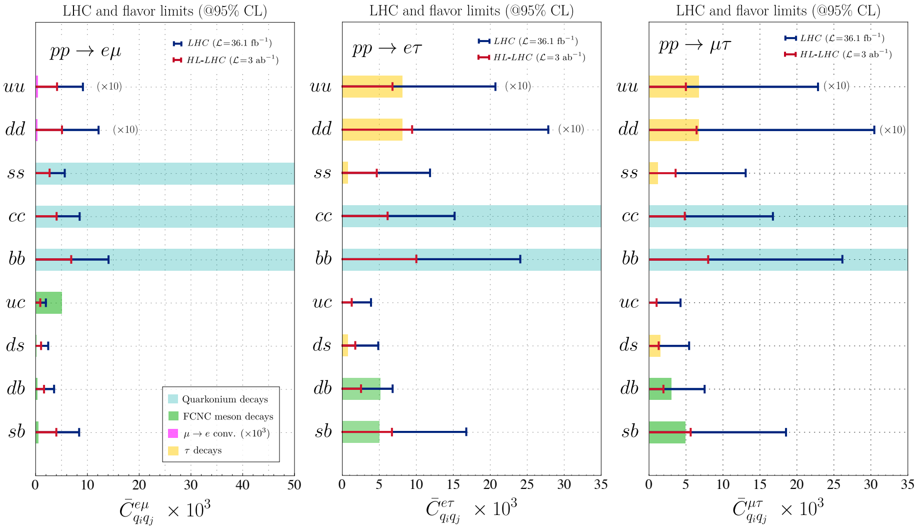
[Angelescu, Faroughy, **OS**. '20]

Recast of $pp \to \mu\tau$ search:

[ATLAS, 1807.06573]

Decay mode	Exp. limit	LHC $(36\ \mathrm{fb}^{-1})$	HL-LHC $(3\ \mathrm{ab}^{-1})$
$B^+ \to K^+\tau\mu$	6.2×10^{-5}	1.5×10^{-3}	2.4×10^{-4}
$\tau \to \mu K^*$	7.7×10^{-8}	3.4×10^{-6}	4.4×10^{-7}
$B^+ \to \pi^+\tau\mu$	9.4×10^{-5}	1.3×10^{-4}	1.1×10^{-5}
$\Upsilon(3S) \to \tau\mu$	4.0×10^{-6}	2.9×10^{-8}	3.4×10^{-9}

NB. Left-handed operators



$$\mathcal{L}_{\text{eff}} = \frac{C^{kl}_{ij}}{v^2} \left(\bar{q}_i \gamma^\mu P_L q_j\right)\left(\bar{\ell}_k \gamma_\mu P_L \ell_l\right)$$

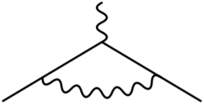
Final remarks: LQs and $(g-2)_\ell$

[Dorsner, Fajfer, **OS**. '19]

Current status of $(g-2)_\ell$

- Long-standing discrepancy $[\approx 3.7\,\sigma]$ in $(g-2)_\mu$:

$$a_\mu^{\rm exp} = 116592089(63)\times 10^{-11}$$
$$a_\mu^{\rm SM} = 116591810(43)\times 10^{-11}$$



[Brookhaven, '06]
[Muon $g-2$ Theory Initiative, '20]

$\Rightarrow$ New results by *Muon* $g-2$ at Fermilab coming soon!

$\Rightarrow$ Ongoing work to understand the leading hadronic contributions (LQCD, dispersive analyses, MuOnE...).

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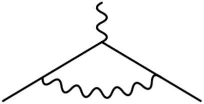

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⇒ New results by *Muon* $g-2$ at Fermilab coming soon!

⇒ Ongoing work to understand the leading hadronic contributions (LQCD, dispersive analyses, MuOnE...).

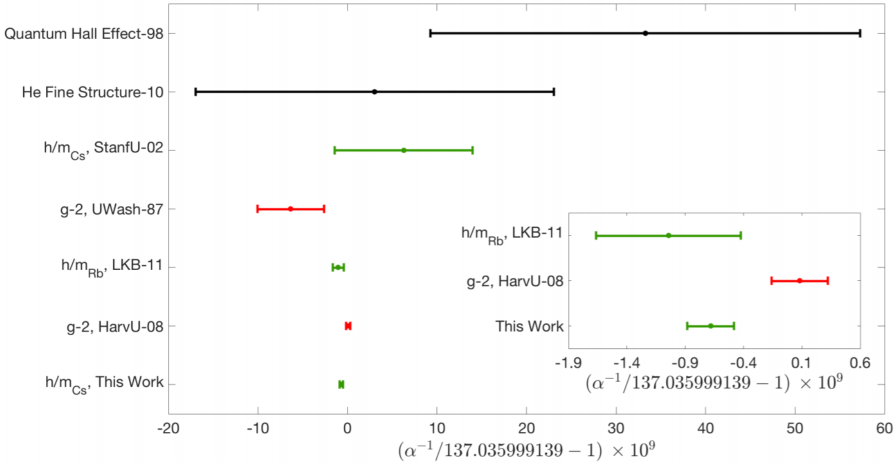
- New determination of α [Cs. '18] shows a $[\approx 2.4\sigma]$ discrepancy in $(g-2)_e$:

$$a_e^{\rm exp} = 1159652180 7.3(2.8) \times 10^{-13}$$
$$a_e^{\rm SM} = 1159652181 6.1(2.3)_{\delta_\alpha}(0.2)_{\rm th} \times 10^{-13}$$

(with the opposite sign!)

⇒ Work in progress to further reduce the error in $(g-2)_e^{\rm exp}$ and $\delta\alpha$.

$(g-2)_e$ no longer gives the best value of α !

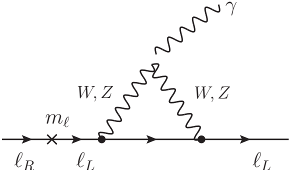


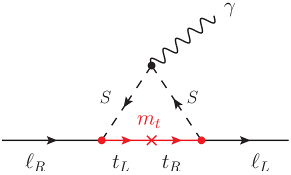
[Parker et al. Science '18]

Leptoquark solutions?

see also [Lindner et al. '16], [Dorsner et al. '19]

- Δa_ℓ $(\ell = e, \mu)$ can be **separately** explained if $\Delta a_\ell \propto \dfrac{m_\ell\, m_t}{\Lambda^2}$:





$\Rightarrow$ LQs should couple to $\overline{\ell_L}\, t_R\, S$ and $\overline{\ell_R}\, t_L\, S$. [Cheung. '01]

$\Rightarrow$ Two viable candidates: $S_1 = (\overline{\mathbf{3}}, \mathbf{1}, 1/3)$ and $R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$.

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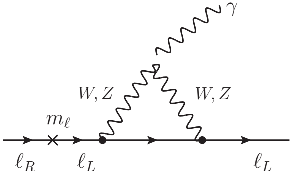

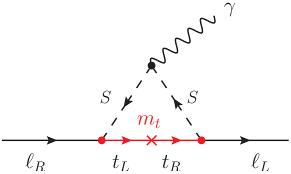

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- Explanation of **both** Δa_e and Δa_μ would imply too large $\mathcal{B}(\mu \to e\gamma)$:

$$\mathcal{B}(\mu \to e\gamma) \gtrsim 5 \times 10^{-5} \left(\frac{|\Delta a_\mu|}{3 \times 10^{-9}}\right) \left(\frac{|\Delta a_e|}{9 \times 10^{-13}}\right)$$

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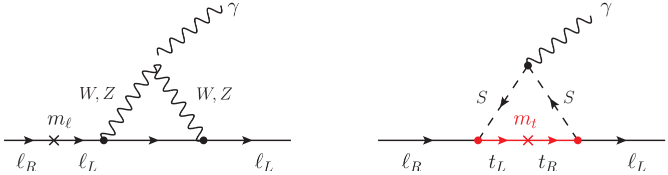

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- In any case, it is difficult to reconcile Δa_e or Δa_μ with B-anomalies...

Summary

- Flavor anomalies are still apparent, but they need strong experimental confirmation.

  Clarification from Belle-II!

- We identify/summarize the viable single mediator explanations to $R_{K^{(*)}}$ and/or $R_{D^{(*)}}$.

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

- U_1 model: we show the complementarity of flavor physics constraints with those obtained from the direct searches at the LHC.

  LHC ditau constraints $\Rightarrow$ lower bound $\mathcal{B}(B \to K\mu\tau) \gtrsim$ few $\times 10^{-7}$

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

  Data-driven model building!

Thank you!

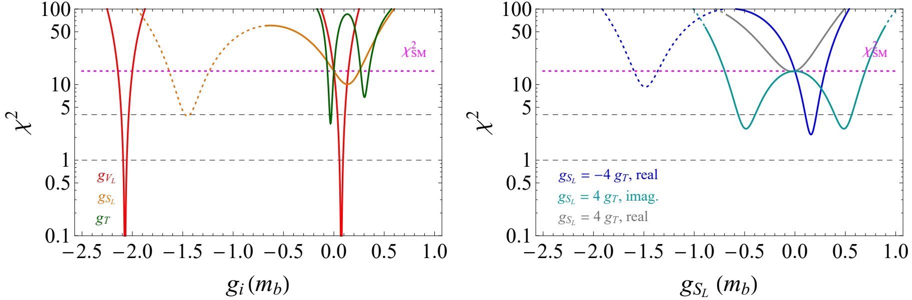
Back-up

[Feruglio, Paradisi, OS. 1806.10155]

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

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

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



[Angelescu, Becirevic, Faroughy, **OS**. 2018]

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]

- In flavor basis

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

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

- In mass-eigenstates basis

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

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

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

and assume

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

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

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}:

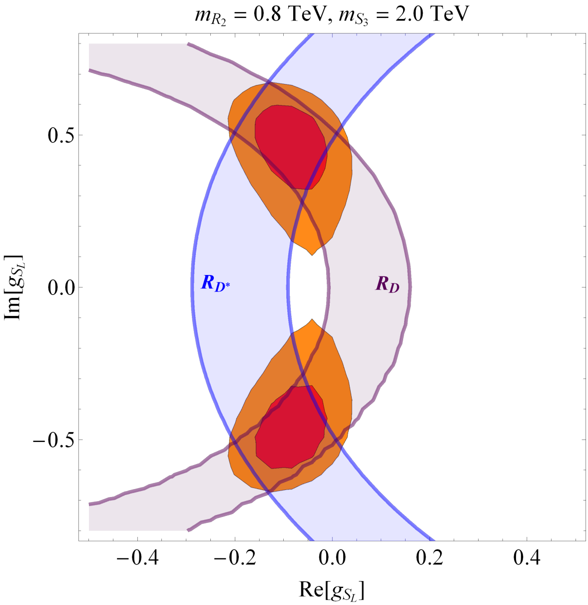
$$\propto \sin^2 2\theta \, \frac{\left[\left(y_L^{c\mu}\right)^2 + \left(y_L^{c\tau}\right)^2\right]^2}{m_{S_3}^2} (\bar{s}_L \gamma^\mu b_L)^2$$

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

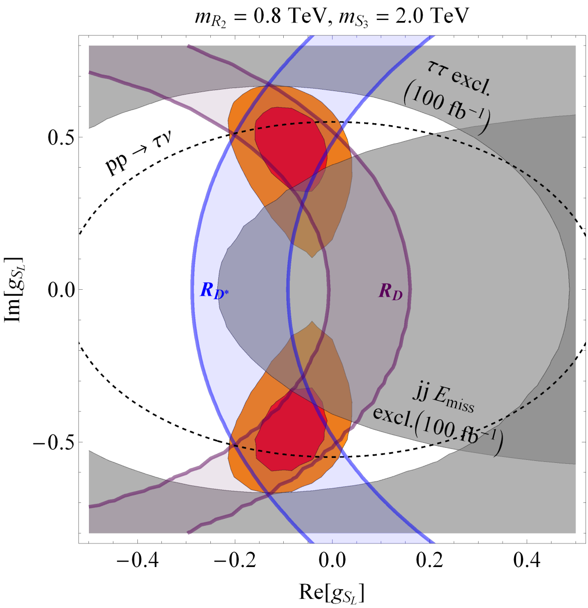
$\Rightarrow$ Phenomenology suggests $\theta \approx \pi/2$ and $y_R^{b\tau}$ complex

Results and predictions:

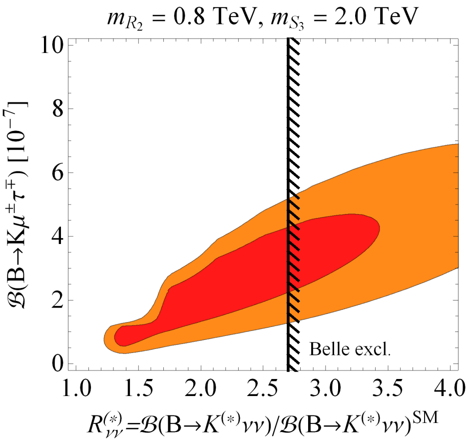
NB. $g_{S_L} = 4\, g_T$



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



Several **distinctive predictions** wrt the SM: R_2 & S_3 GUT



- **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?

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]

Branching fractions and other results LHCb-Paper-2019-009

Imperial College London

If instead the Run 1 and Run 2 were fitted separately:

$$R_{K\ \mathrm{Run\ 1}}^{\mathrm{new}} = 0.717^{+0.083}_{-0.071}{}^{+0.017}_{-0.016}, \quad R_{K\ \mathrm{Run\ 2}} = 0.928^{+0.089}_{-0.076}{}^{+0.020}_{-0.017},$$

$$R_{K\ \mathrm{Run\ 1}}^{\mathrm{old}} = 0.745^{+0.090}_{-0.074} \pm 0.036 \quad \text{(PRL113(2014)151601)},$$

Compatibility taking correlations into account:

- Previous Run 1 result vs. this Run 1 result (new reconstruction selection): $< 1\,\sigma$;
- Run 1 result vs. Run 2 result: $1.9\,\sigma$.

$B^+ \to K^+\mu^+\mu^-$ **branching fraction**:

- Compatible with previous result (JHEP06(2014)133) at $< 1\,\sigma$;
- Run 1 and Run 2 results compatible at $< 1\,\sigma$.

$B^+ \to K^+e^+e^-$ **branching fraction**:

$$\frac{\mathrm{d}\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathrm{d}q^2}(1.1 < q^2 < 6.0\ \mathrm{GeV}^2) = (28.6^{+2.0}_{-1.7} \pm 1.4) \times 10^{-9}\ \mathrm{GeV}^{-2}$$

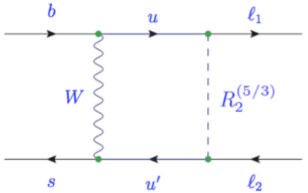
Moriond EW '19

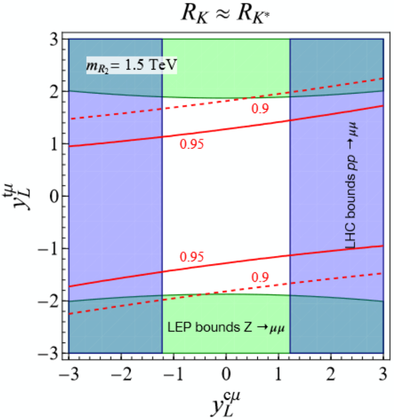
$$R_2 = (3, 2, 7/6) \qquad \mathcal{L}_{R_2} = y_R^{ij}\, \overline{Q}_i \ell_{Rj}\, R_2 - \boxed{y_L^{ij}\, \overline{u}_{Ri} R_2 i\tau_2 L_j} + \text{h.c.}$$

$$C_9^{kl} = C_{10}^{kl} \overset{\text{tree}}{=} -\frac{\pi v^2}{2V_{tb}V_{ts}^*\alpha_{\text{em}}} \frac{y_R^{sl}\left(y_R^{bk}\right)^*}{m_{R_2}^2}$$

$$C_9^{kl} = -C_{10}^{kl} \overset{\text{loop}}{=} \sum_{u,u' \in \{u,c,t\}} \frac{V_{ub}V_{u's}^*}{V_{tb}V_{ts}^*} y_L^{u'k} \left(y_L^{ul}\right)^* \mathcal{F}(x_u, x_{u'})$$

$$\boxed{y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & 0 \\ 0 & y_L^{t\mu} & 0 \end{pmatrix}}, \qquad y_R = 0$$





Update of [Becirevic, **OS**. '17]

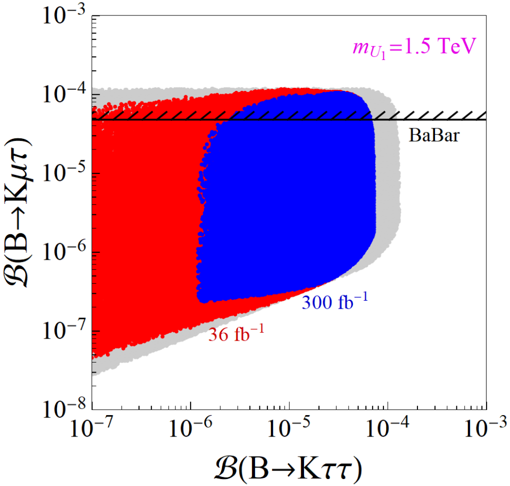
Limits on LQ pair-production

[Angelescu, Becirevic, Faroughy, **OS**. 1808.08179]

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

How about $b \to s\tau\tau$?

see e.g. [Buttazzo et al. '17, Capdevila et al. '17]



⇒ Large enhancement of e.g. $\mathcal{B}(B \to K\tau\tau)^{\text{SM}}_{[15,22]} = 1.20(12) \times 10^{-7}$

⇒ Can it be tested experimentally?

How to probe $b \to s\tau\tau$?

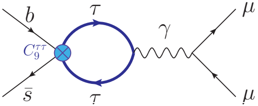
e.g. $C_9^{\tau\tau} = -C_{10}^{\tau\tau}$

- Existing direct limits:

$$\mathcal{B}(B \to K\tau\tau)^{\text{exp}} < 2.2 \times 10^{-3} \quad \text{[BaBar. '17]}$$
$$\mathcal{B}(B_s \to \tau\tau)^{\text{exp}} < 6.8 \times 10^{-3} \quad \text{[LHCb. '17]}$$

still far from SM predictions ($\approx 10^{-7}$). Perhaps at FCC-ee?

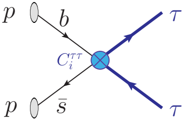
- New idea: deformation of $B \to K\mu\mu$ q^2-spectrum



$$\mathcal{B}(B \to K\tau\tau) \lesssim 2.3 \times 10^{-3} \quad \text{[preliminary]}$$

[M. König, LHCb Implications '19]

- Also promising: $pp \to \tau\tau$ at high-p_T



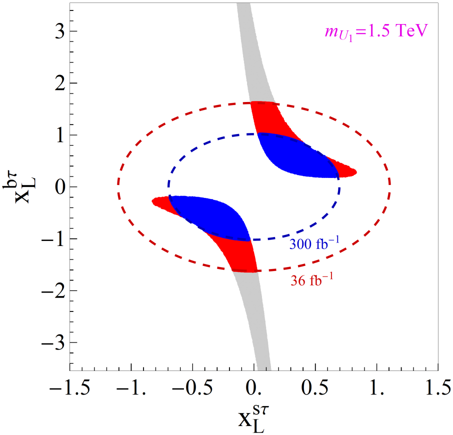
$$\mathcal{B}(B \to K\tau\tau) \lesssim 1.1 \times 10^{-3} \qquad (36.1\ \text{fb}^{-1})$$
$$\mathcal{B}(B \to K\tau\tau) \lesssim 1.4 \times 10^{-5} \qquad (3\ \text{ab}^{-1})$$

[Angelescu, Faroughy, **OS**. To appear]

but more model dependent (EFT validity?)

Take-home: Different approaches are complementary!

Combining low and high-energy constraints $U_1 = (3, 2, 1/3)$



$R_{D^{(*)}}$ depends on:

$$g_{V_L} = \frac{v^2}{2m_{U_1}^2}\left(x_L^{b\tau}\right)^* \left(x_L^{b\tau} + \frac{V_{cs}}{V_{cb}} x_L^{s\tau}\right)$$

Same couplings probed by $\underline{pp \to \tau\tau}$: 36 fb^{-1} (blue) and 300 fb^{-1} (red).

$\Rightarrow$ Upper limit on $|x_L^{b\tau}|$ implies a nonzero lower limit on $|x_L^{s\tau}|$!

[C. Marin Benito, talk at Epiphany '20].

Observables of interest

First test of LU with b-baryons, using $\mathbf{\Lambda_b \to pK^-\mu^+\mu^-}$ and $\mathbf{\Lambda_b \to pK^-e^+e^-}$ decays:

$$R_{pK}^{-1} = \frac{\mathcal{B}(\Lambda_b^0 \to pK^- e^+ e^-)}{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi(\to e^+e^-))} \Big/ \frac{\mathcal{B}(\Lambda_b^0 \to pK^- \mu^+ \mu^-)}{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+\mu^-))}$$

in the region:

- $0.1 < q^2 < 6$ GeV/c^4
- m(pK) < 2.6 GeV/c^2

* Inverse definition due to expected small yields in rare electron mode

- $\Lambda_b \to pK^-e^+e^-$ never observed before → first observation
- $B(\Lambda_b \to pK^-\mu^+\mu^-)$ never measured before → first measurement

[C. Marin Benito, talk at Epiphany '20]

arXiv:1912.0813

Summary & conclusions

First test of LU performed with b-baryons R^{-1}_{pK}

- result compatible with unity
- and with previous R_H measurements
- null test of the SM → larger stats are needed

With more data:

- study m(pK) spectrum
- split q^2 ranges for higher sensitivity

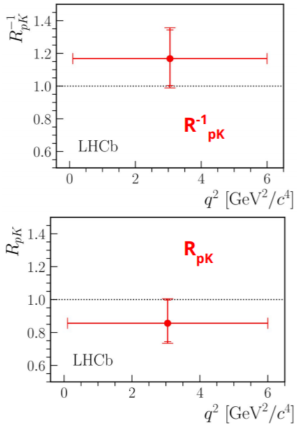
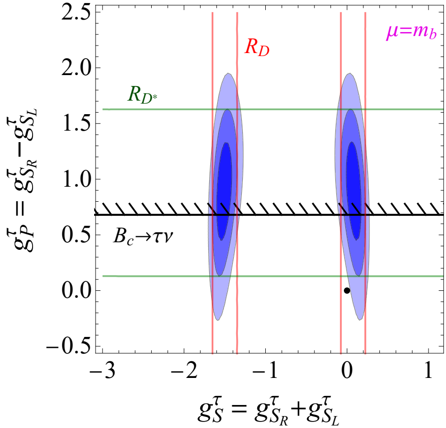


Illustration: a) (pseudo)scalar operators

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

$$\mathcal{O}_{S_R} = (\bar{c}_L b_R)(\bar{\ell}_R \nu_L)$$



NB.

$$\langle D|\bar{c}\gamma_5 b|B\rangle = \langle D^*|\bar{c}b|B\rangle = 0$$

$\Rightarrow$ Tension with τ_{B_c} constraint: $\mathcal{B}(B_c \to \tau\bar{\nu}) \lesssim 30\%$

$$\mathcal{B}(B_c \to \tau\bar{\nu}) = \frac{\tau_{B_c} m_{B_c} f_{B_c}^2 G_F^2 |V_{cb}|^2}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2 \left|1 + g_P \frac{m_{B_c}^2}{m_\tau (m_b + m_c)}\right|^2$$

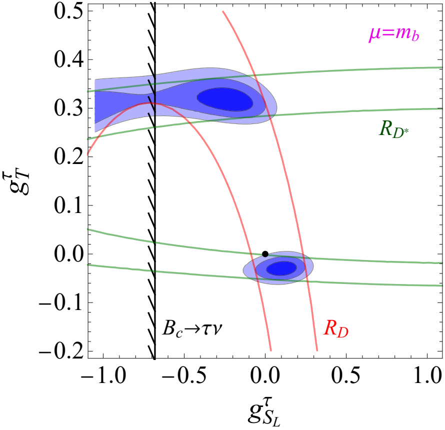
[Alonso et al. 16'], see also [Akeroyd et al. 17']

Illustration: b) scalar/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]



⇒ R_{D^*} is highly sensitive to tensor contributions

⇒ Scalar and tensor operators provide a good fit – case of scalar leptoquarks $S_1 = (\bar{3}, 1, 1/3)$ and $R_2 = (3, 2, 7/6)$. τ_{B_c} is not a problem here!

More **exp. information** is **needed** to distinguish among them!

i) Many angular/polarization observables

[Becirevic et al. '16]

First measurements:

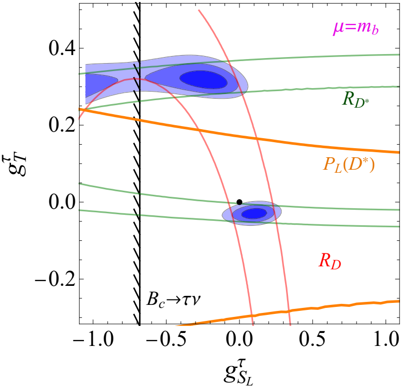
- $P_\tau(D^*)^{\rm exp} = -0.38 \pm 0.51^{+0.21}_{-0.16}$ [Belle '17]
- $F_L(D^*)^{\rm exp} = 0.60 \pm 0.08 \pm 0.03$ [Belle '18]

First measurement by Belle: [Belle preliminary, '18]

$$F_L(D^*)^{\rm exp} = \frac{\mathcal{B}(B\to D^*_L \tau\bar\nu)}{\mathcal{B}(B\to D^*\tau\bar\nu)} = 0.60(8)(3)$$

⇒ Consistent with SM prediction $F_L(D^*)^{\rm SM} \approx 0.46(4)$; large exp error

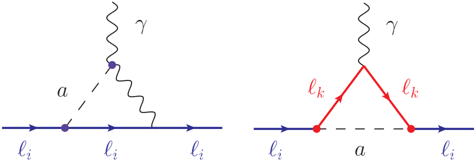
⇒ Already useful to distinguish among NP scenarios: [Aebischer et al. '18]



Proof of feasibility for Belle-II! [Becirevic, Jaffredo, Peñuelas, **OS**. In preparation.]

ALPs for $(g-2)_\ell$

$$\mathcal{L}_{\rm eff}^{d\leq 5} \supset c_{\gamma\gamma}\frac{a}{\Lambda}F_{\mu\nu}\widetilde{F}^{\mu\nu} + \sum_{ij} a_{ij}^{\ell}\,\frac{\partial_\mu a}{\Lambda}\,\bar{\ell}_i\gamma^\mu\gamma_5\ell_j + \dots$$



$$\Delta a_{\ell_i} = (\Delta a_{\ell_i})_{\rm LFC} + (\Delta a_{\ell_i})_{\rm LFV}$$

- Barr-Zee diagram [left] can account for $(g-2)_\mu$: [Marciano et al. '16]

$$(\Delta a_\mu)_{\rm LFC} \propto \frac{m_\mu^2}{\Lambda^2}\,a_{\mu\mu}^{\ell}\,a_{\gamma\gamma}\,\log\frac{\Lambda}{m_a} + \dots$$

- LFV contributions to $(g-2)_e$ [right] are chirality-enhanced:

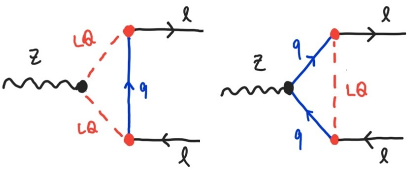
$$(\Delta a_e)_{\rm LFV} \propto \frac{m_\tau m_e}{\Lambda^2}\,|a_{e\tau}^{\ell}|^2$$

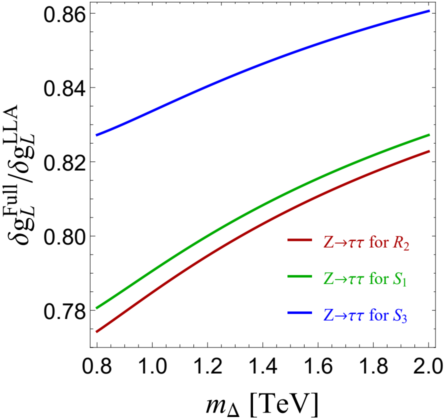
$\Rightarrow$ Both anomalies can be explained with reasonable couplings.

$Z \to \ell\ell$ beyond leading logarithms

Full computation:

[Arnan, Becirevic, Mescia, **OS**. '19]





To be compared with leading log approximation (LLA).

[Feruglio et al. '16]

$\Rightarrow$ $\mathcal{O}(20\%)$ corrections due to external momenta ($\propto x_Z \log x_t$) and finite terms not considered before

cf. e.g. [Neubert et al. '15], [Buttazo et al. '17] + many more!