B-physics anomalies: a road to new physics?

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In collaboration with

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Motivation

Several discrepancies [$\approx 2-3\sigma$] appeared recently in B-meson decays:

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

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

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

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

Outline

i) Introduction

ii) Brief overview of the B-physics anomalies

iii) EFT implications

iv) From EFT to simplified models

v) Closing the leptoquark window

vi) What about $(g-2)_\ell$?

Introduction

Why are they interesting?

- Significant (and unexpected!) pattern of deviations.

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- Neutrino oscillation
- Dark Matter*
- Baryon asymmetry (BAU)*
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- Hierarchy problem
- Flavor problem
- Strong CP-problem
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- Most of the theoretical effort so far was dedicated to the Higgs hierarchy problem.
- If confirmed, they will indicate the existence of new sources of flavor violation at the TeV scale

  $\Rightarrow$ Paradigm shift (with far-reaching implications!)

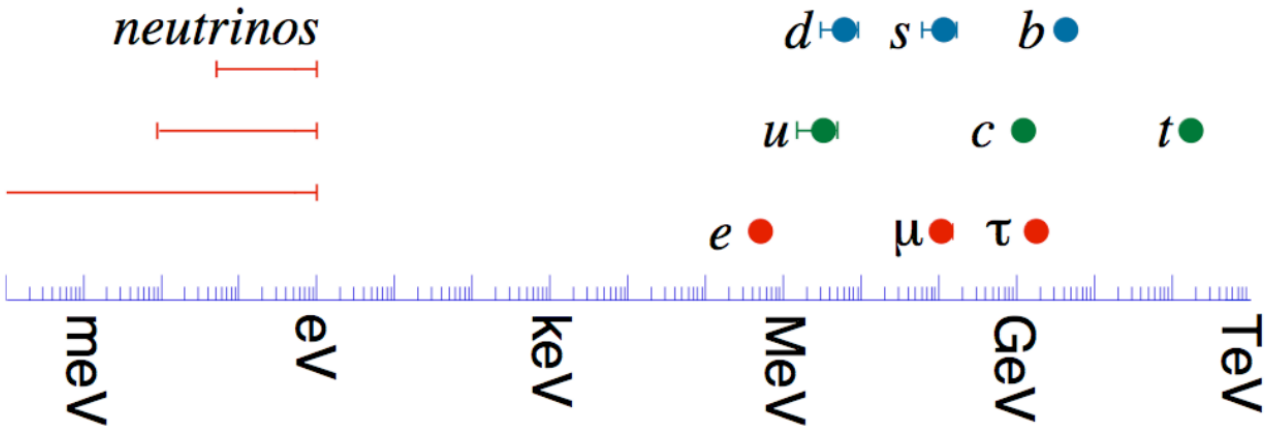
Origin of flavor?

- Flavor sector **loose**:

  $\Rightarrow$ 13 free parameters (masses and quark mixing) – fixed by data.

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

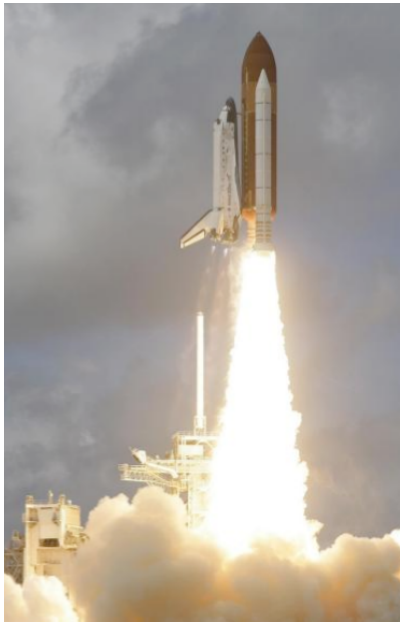
- Striking hierarchy *[does not look accidental...]* $\Rightarrow$ Flavor theory?



- Is there a Flavor Era around the corner?

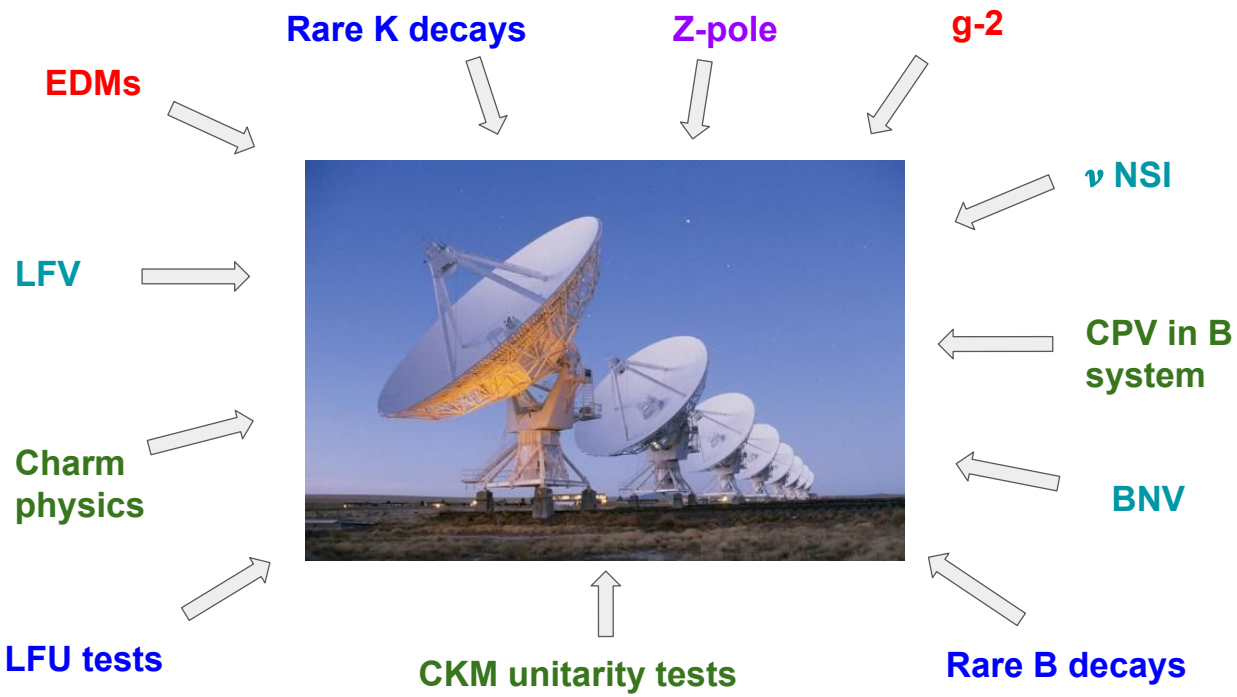
Seeking new physics through flavor observables

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.

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-$\overline{B}^0$ 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
$m_b < 5 GeV/c^2$	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]
$m_t > 50 GeV/c^2$	t quark mass

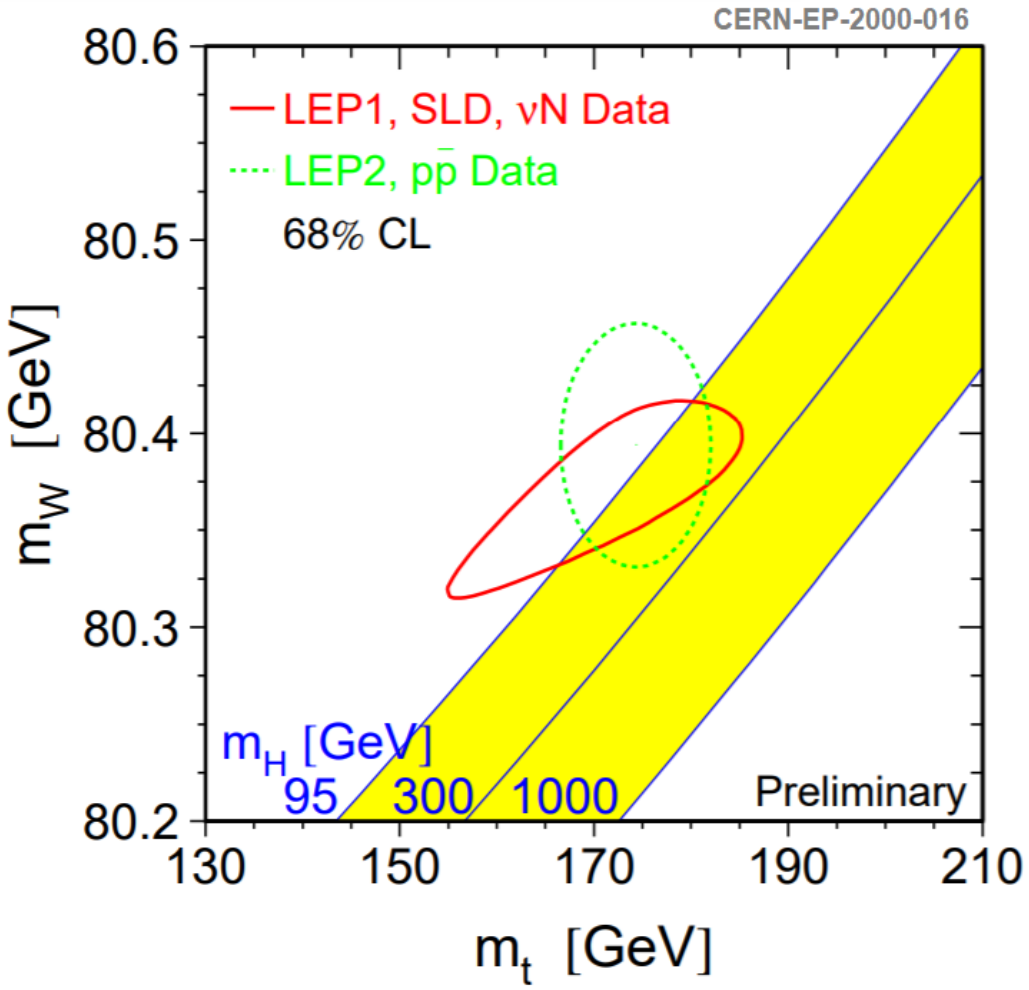
GIM mechanism:

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

Grossman and 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!

Electroweak precision at LEP

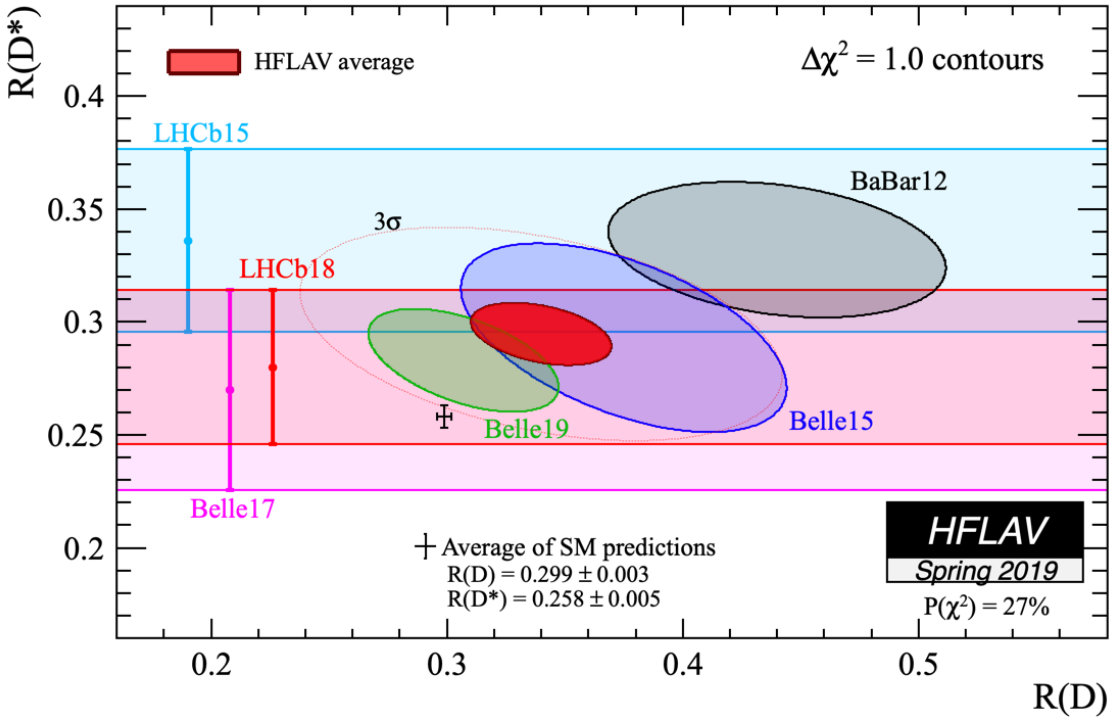


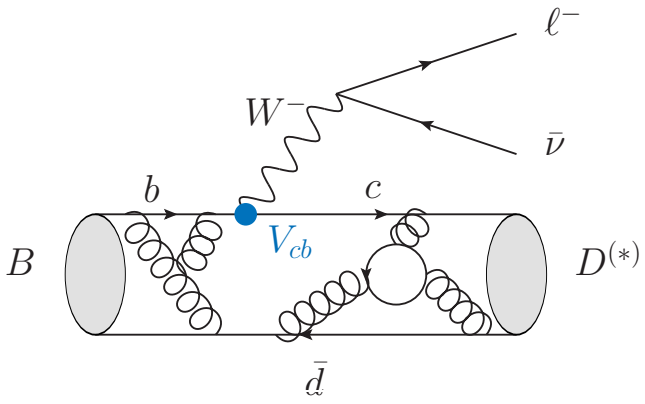
⇒ Top-quark discovery: combined effort of direct and indirect searches.

Brief overview of the B-anomalies

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

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

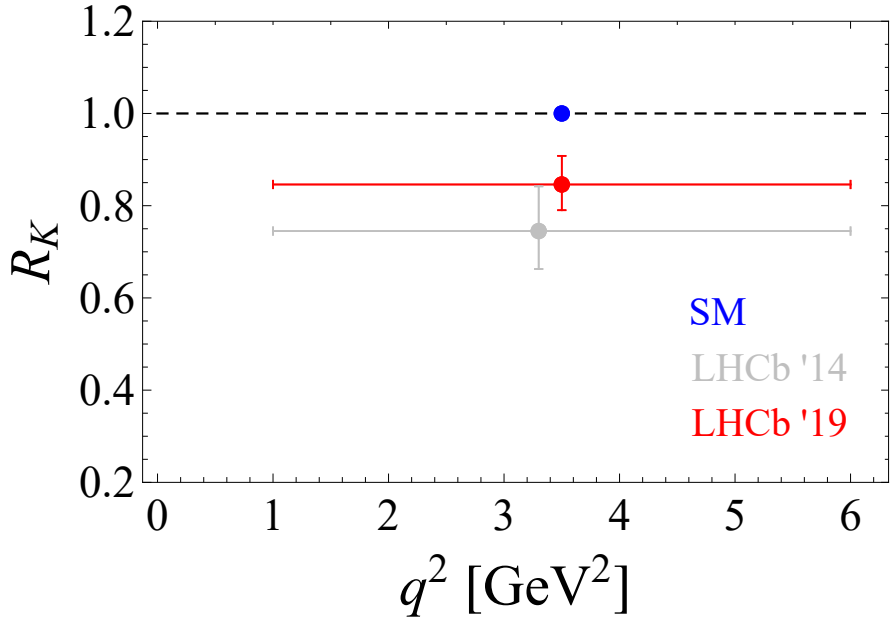
with $f_+(0) = f_0(0)$.

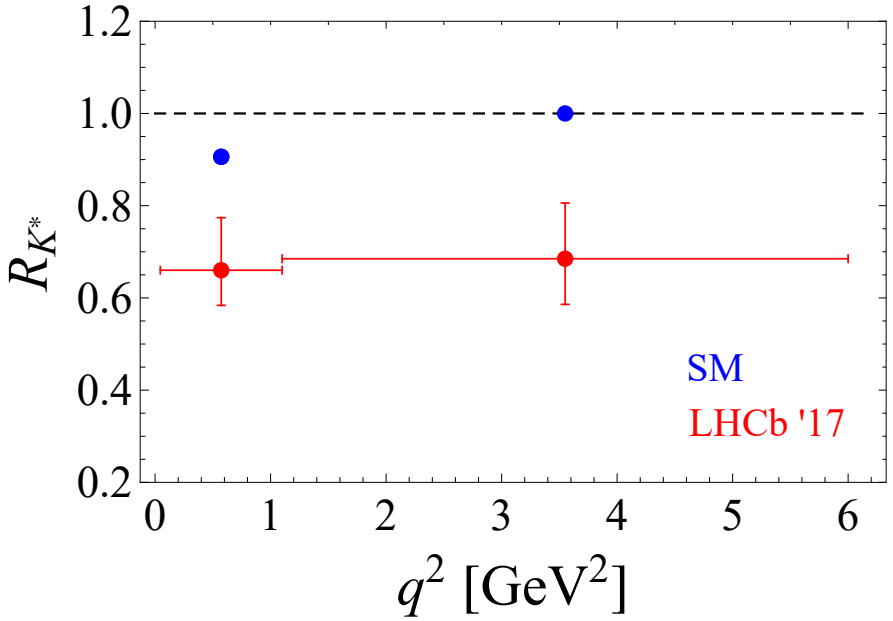
- R_{D^*}: lattice QCD at $q^2 \neq q^2_{\rm max}$ not available, scalar form factor $[A_0(q^2)]$ never computed on the lattice

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 $[\approx 4\sigma]$





$\Rightarrow$ **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, $R_{K^{(*)}} = 1.00(1)$. [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 $\Longrightarrow$ EFT $\Longrightarrow$ Simplified model $\Longrightarrow$ UV completion

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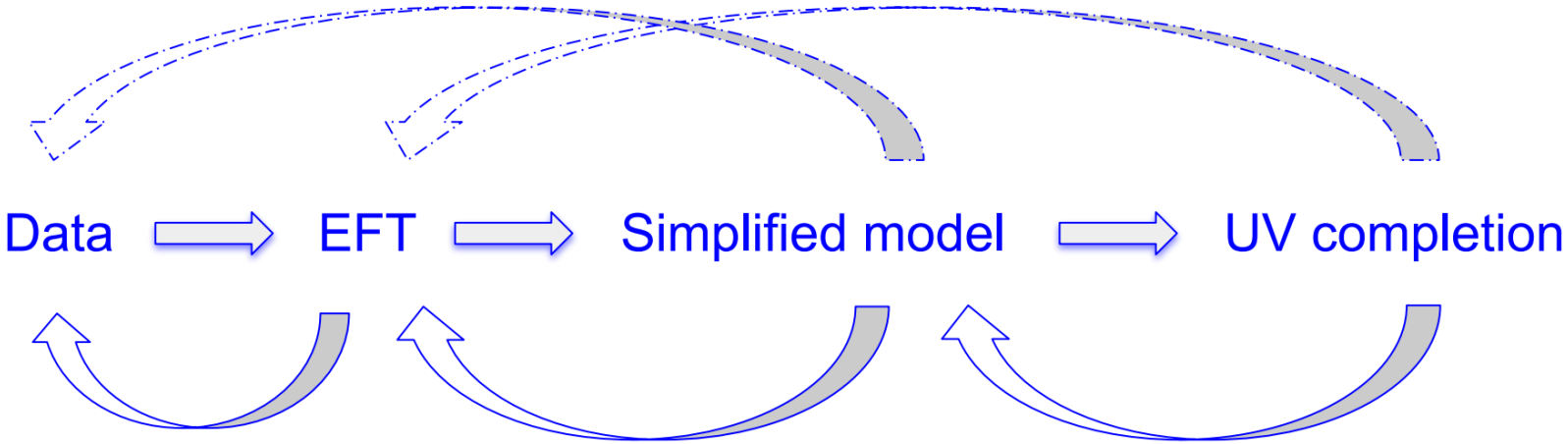
Data-driven approach:



EFT interpretations

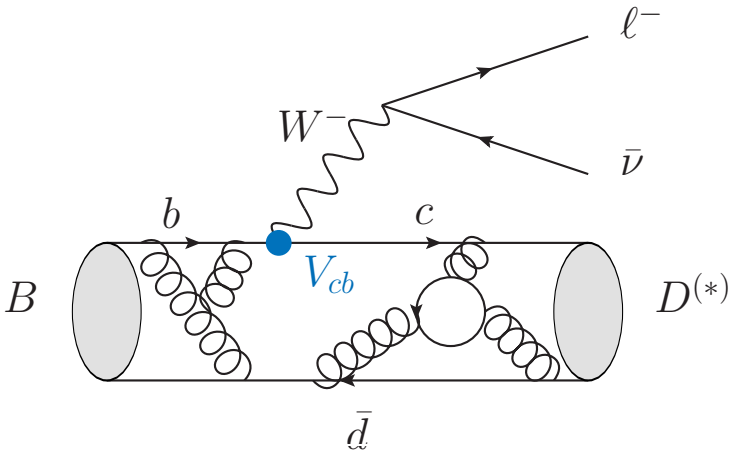
[Angelescu, Becirevic, Faroughy, **OS**. 1808.08179]

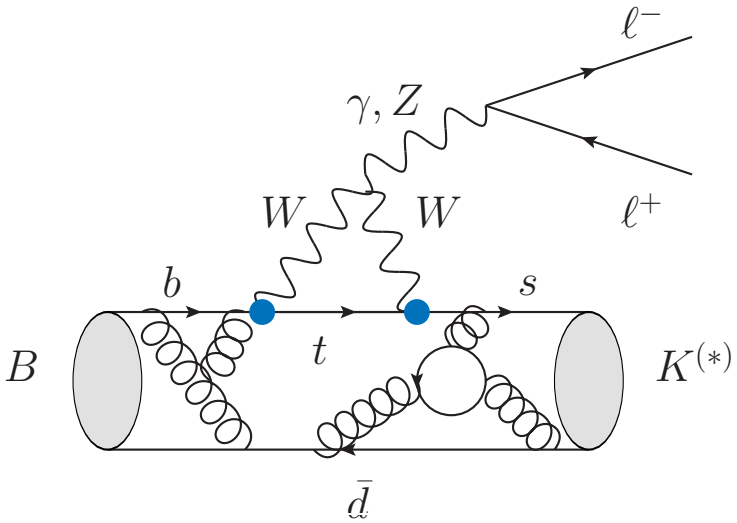
[Feruglio, Paradisi, **OS**. 1806.10155]

...

What is the **scale of New Physics**?

- $R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}} \quad \Rightarrow \quad \Lambda_{\rm NP} \lesssim 3$ TeV [perturbative couplings]
- $R^{\rm exp}_{K^{(*)}} < R^{\rm SM}_{K^{(*)}} \quad \Rightarrow \quad \Lambda_{\rm NP} \lesssim 30$ TeV see also [Di Luzio et al. 2017]





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!

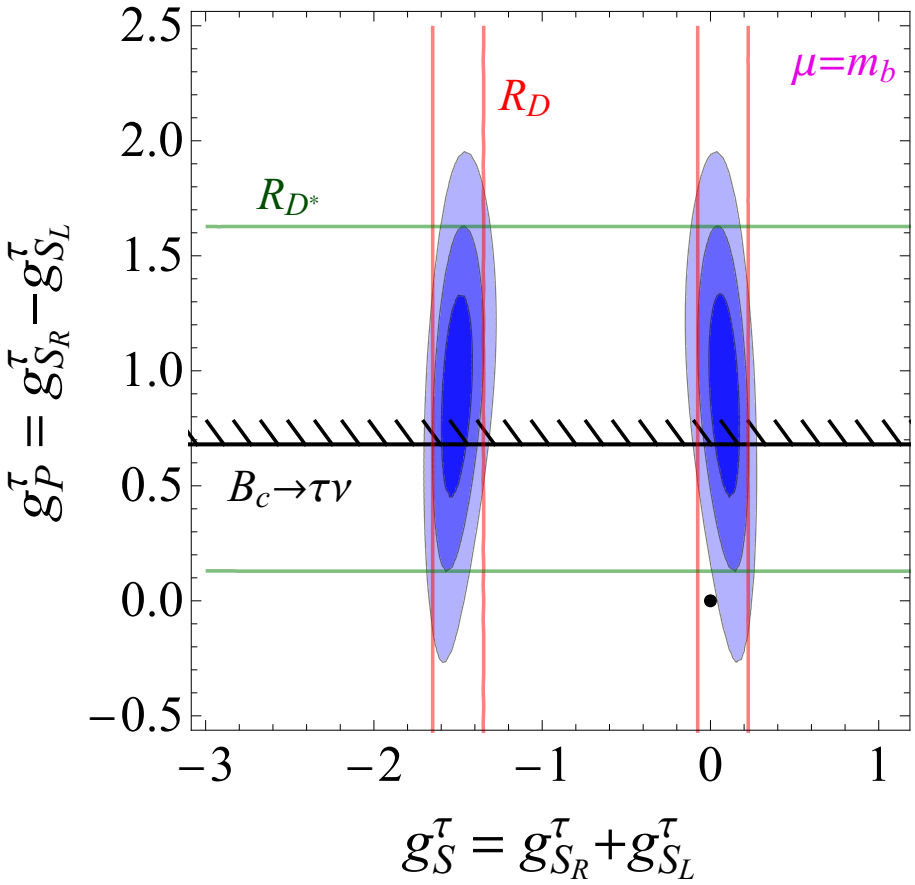
[Angelescu, Becirevic, Faroughy, **OS**. 1808.08179]

see also [Murgui et al. '19, Shi et al. '19, Blanke et al. '19]

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: $\mathcal{B}(B_c \to \tau\bar{\nu}) \lesssim 30\%$

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

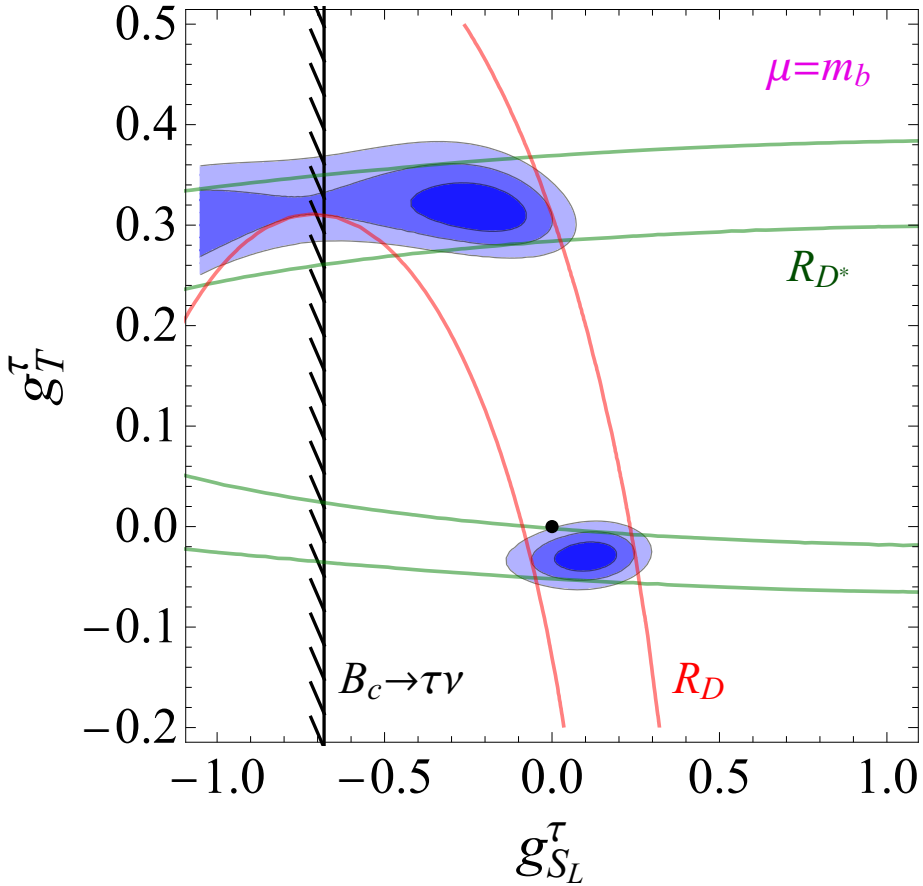
[Alonso et al. 16'], see also [Akeroyd et al. 17']

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]



$\Rightarrow$ R_{D^*} is highly sensitive to tensor contributions

$\Rightarrow$ 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!

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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]

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

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

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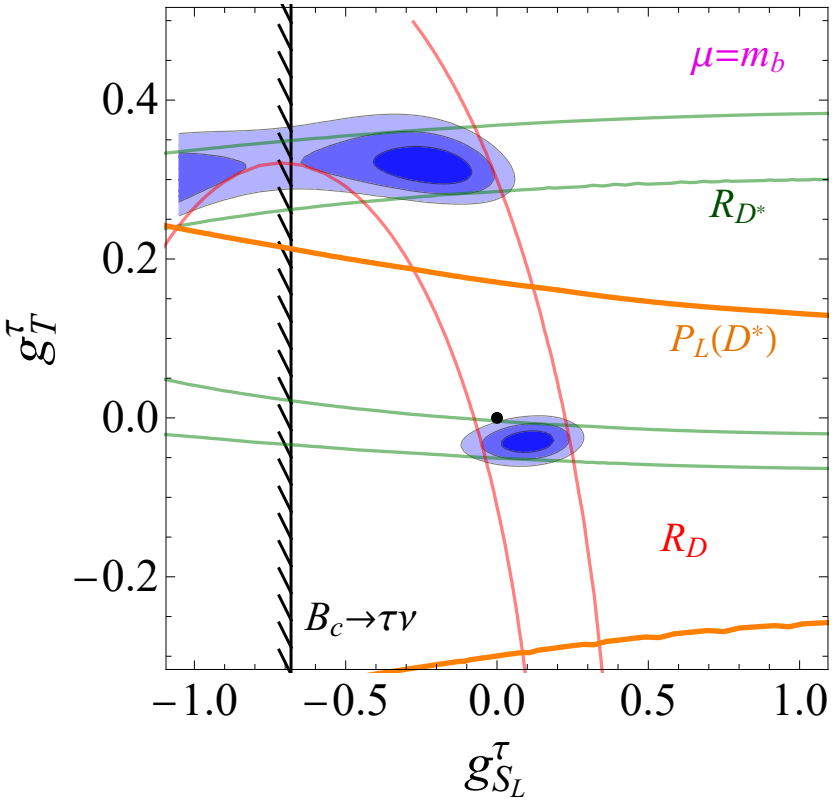
⇒ Already useful to distinguish among NP scenarios: [Aebischer et al. '18]



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

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ii) Other LFUV ratios:

[cf. back-up]

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

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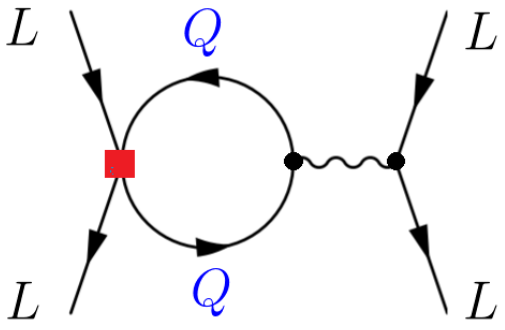
iii) Electroweak observables (via electroweak RGE effects)

- $\mathcal{B}(Z \to \tau\tau)/\mathcal{B}(Z \to \mu\mu)$
- $\mathcal{B}(\tau \to \mu\nu\bar{\nu})$
- $\mathcal{B}(h \to \tau\tau)$

[Feruglio et al.'17]
[Feruglio, Paradisi, **OS**. 1806.10155]

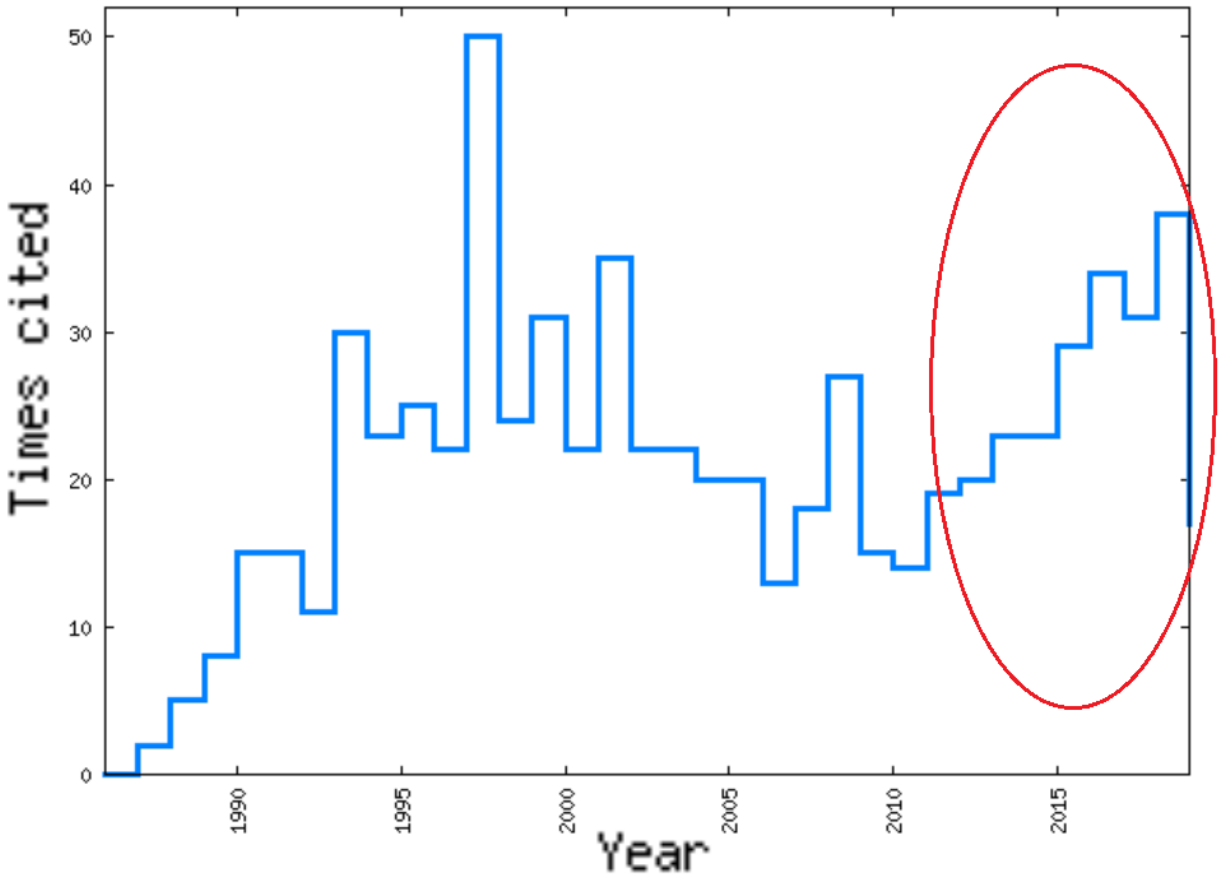
e.g.



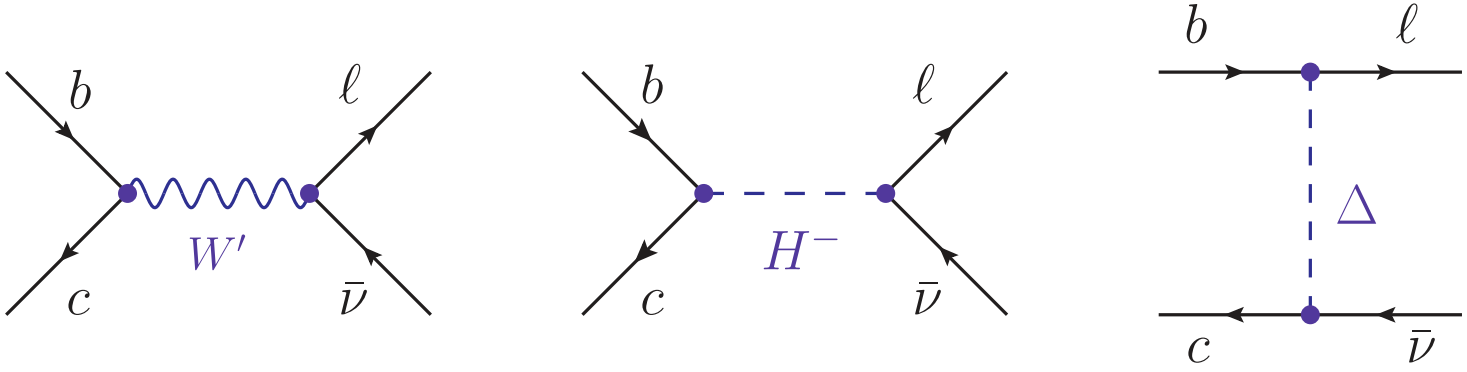
From EFT to simplified models: Why leptoquarks?

Citation history:

[Buchmuller, Ruckl. '87]



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



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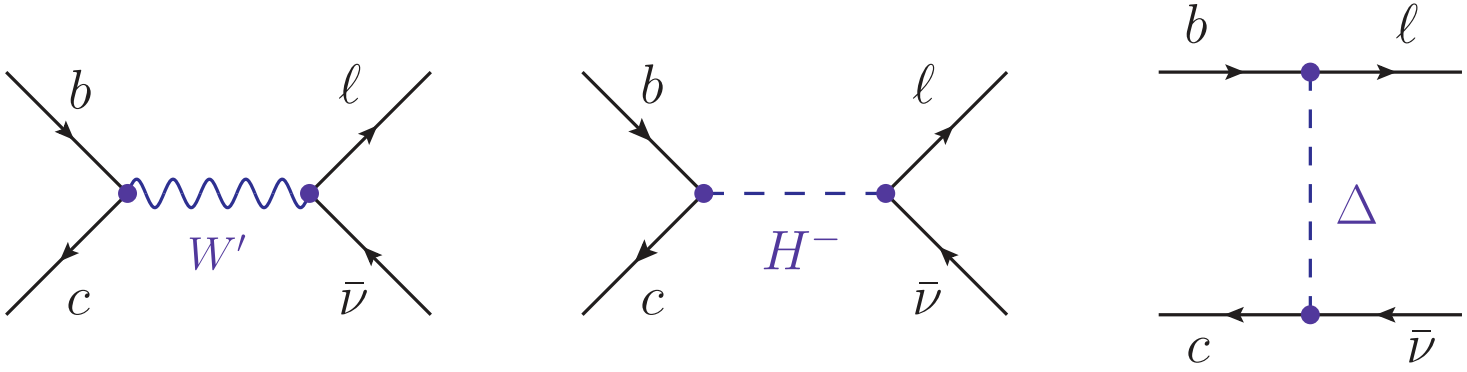

Challenges for New Physics:

- 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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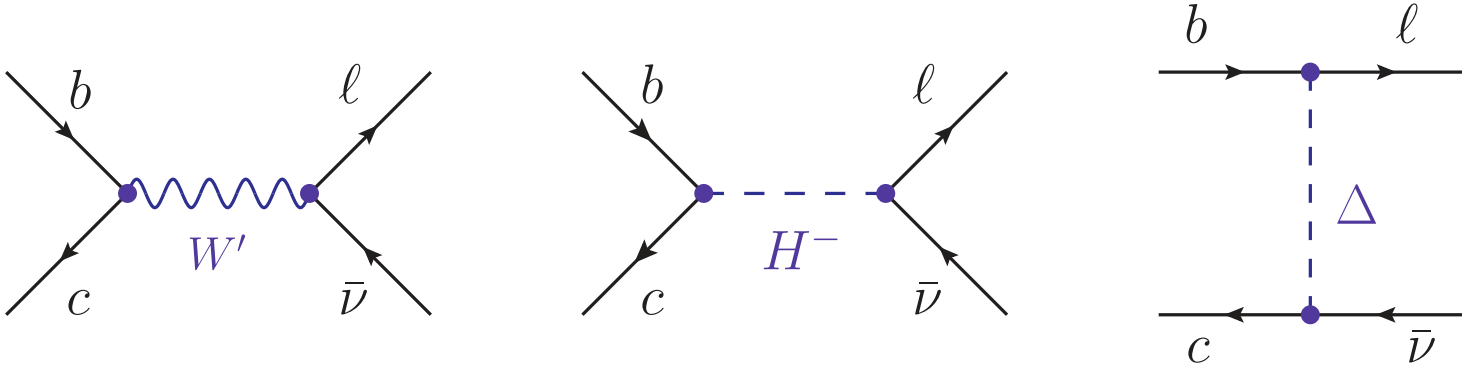

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In Summary:

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

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

NB. w/o ν_R

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

Viable models: [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 $b \to c\ell\nu$ observables!

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

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

- 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]

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

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

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

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu\gamma^5 \ell)$$
$$\mathcal{O}_S^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\ell) \qquad \mathcal{O}_P^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell)$$
$$\mathcal{O}_7^{(\prime)} = m_b(\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$

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

[Buchmuler, Wyler. '85]

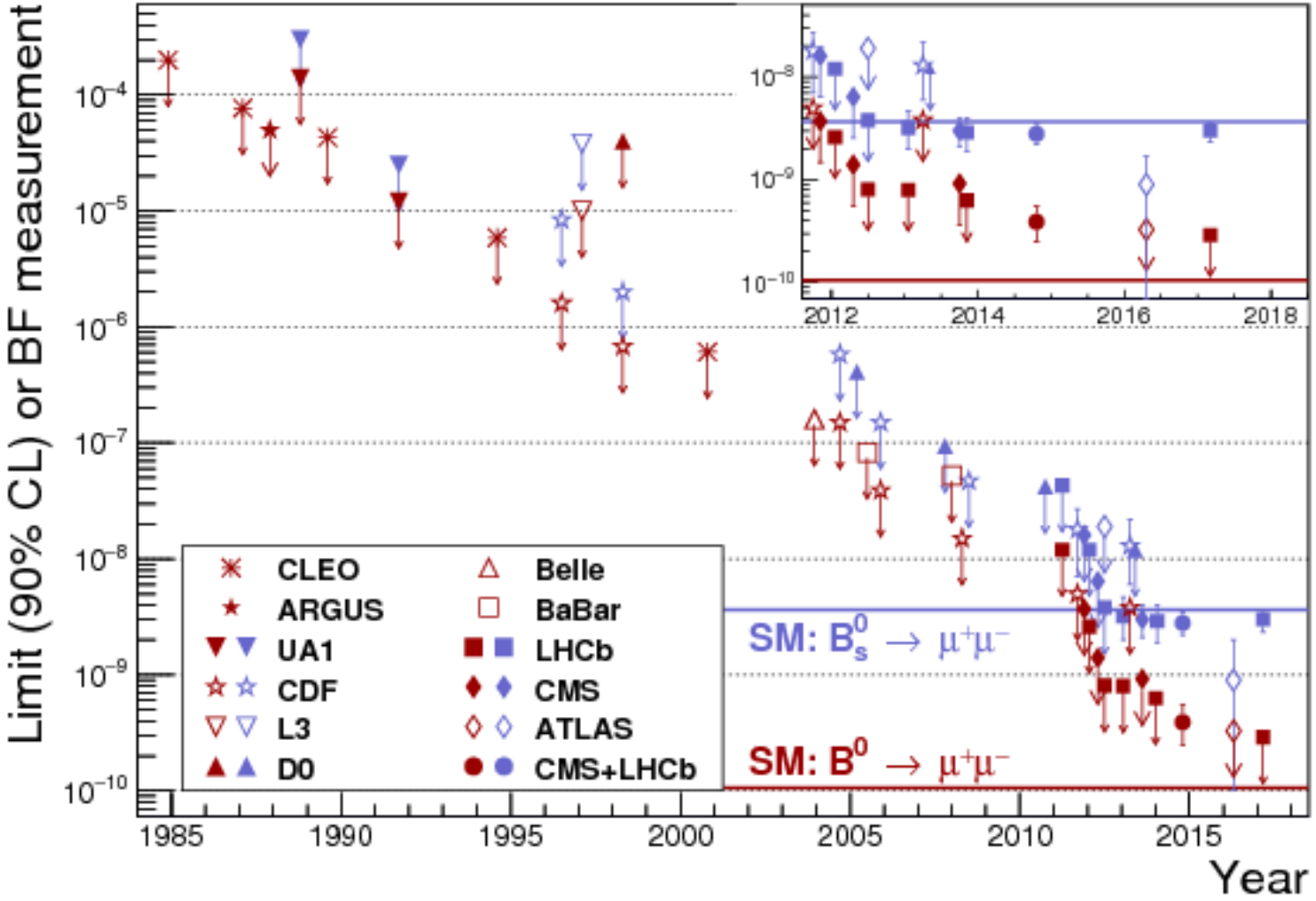
- (Pseudo)scalar operators are tightly constrained by

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

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

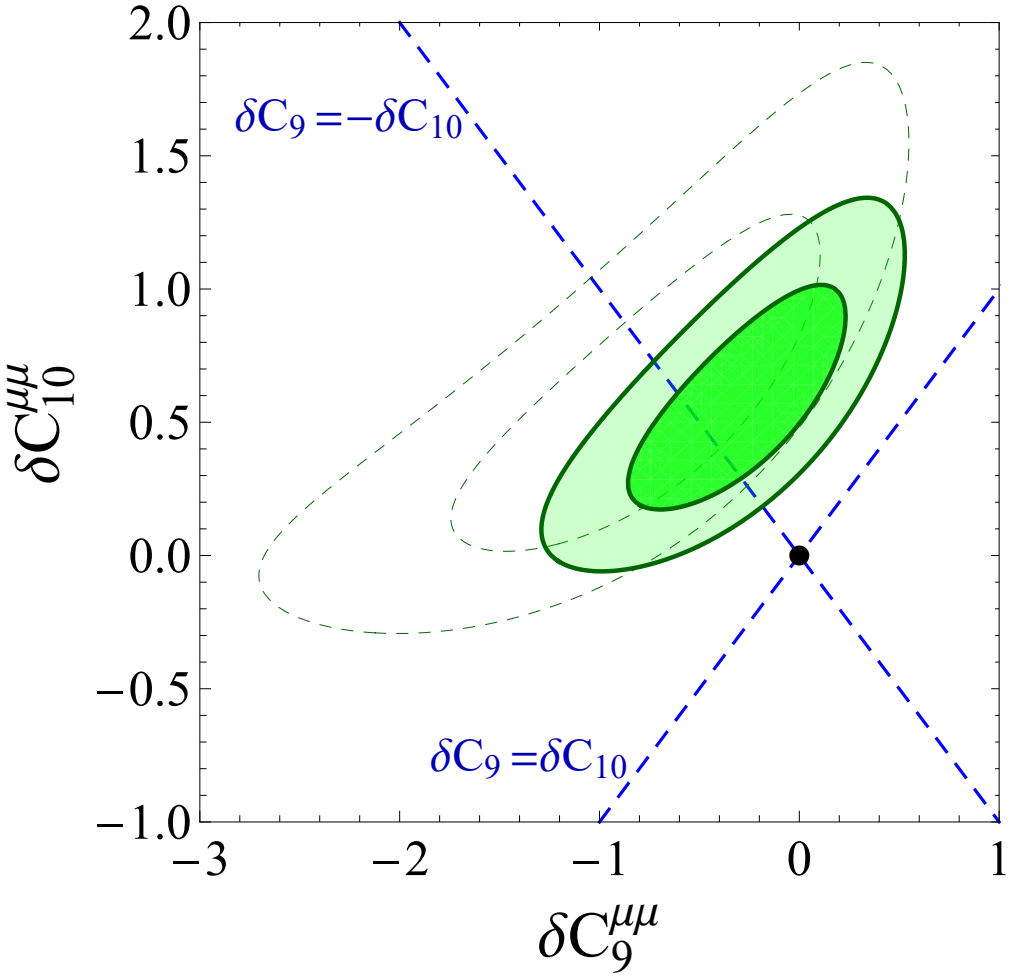
A long journey...

[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 $R_{K^*}^{\rm exp} < R_{K^*}^{\rm SM}$.
- $C_9 = -C_{10}$ 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. [Capdevilla et al. '19], [Aebischer et al. '19], [Arbey et al.]...

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.

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

  $\Rightarrow$ Viables TeV models proposed: $U_1 + Z' + g'$ (more than one mediator!)

  [Di Luzio et al. '17, Bordone et al. '17...].

- Two scalar LQs are also viable:

  $\Rightarrow S_1$ and S_3 [Crivellin et al. '17, Marzocca. '18], R_2 and S_3 [Becirevic et al. '18].

Closing the leptoquark window:

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

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

Setup

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

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

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

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

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

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

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

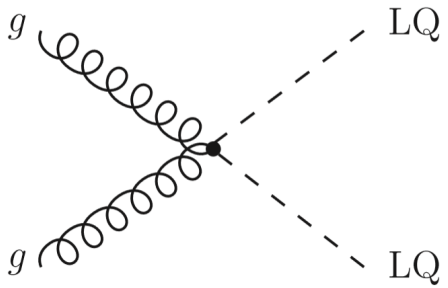
- Other observables: $\tau \to \mu\phi$, $B \to \tau\bar{\nu}$, $D_{(s)} \to \mu\bar{\nu}$, $D_s \to \tau\bar{\nu}$, $K \to \mu\bar{\nu}/K \to e\bar{\nu}$, $\tau \to K\bar{\nu}$ and $B \to D^{(*)}\mu\bar{\nu}/B \to D^{(*)}e\bar{\nu}$.

LHC constraints

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

- LQ pair-production via QCD:

[CMS-PAS-EXO-17-003]

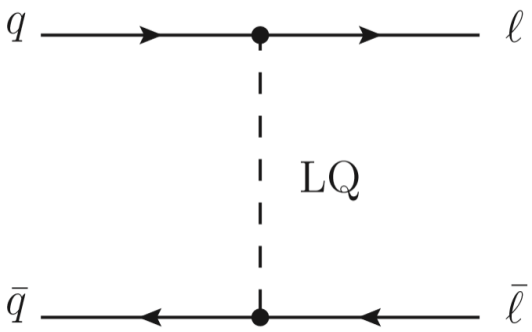


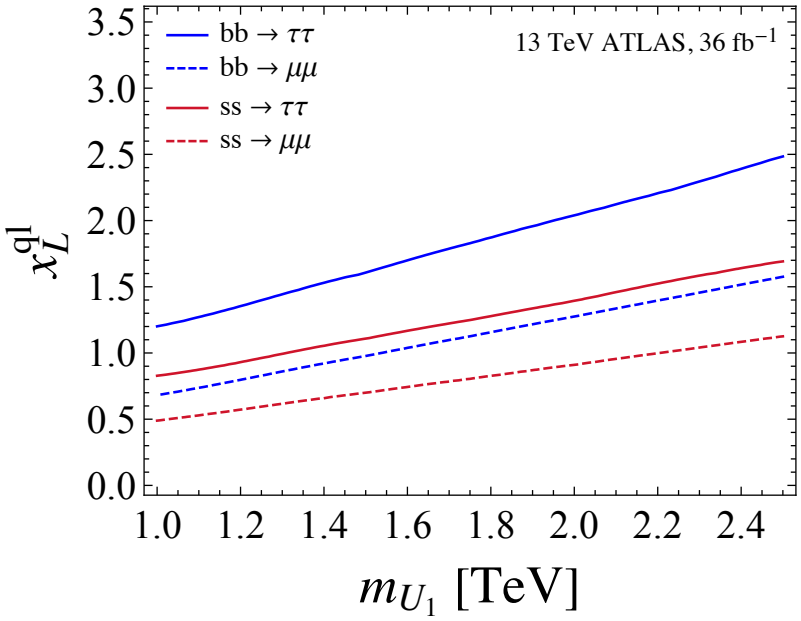
$m_{U_1} \gtrsim 1.5$ TeV

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

- Di-lepton tails at high-pT:

[ATLAS. 1707.02424,1709.07242]

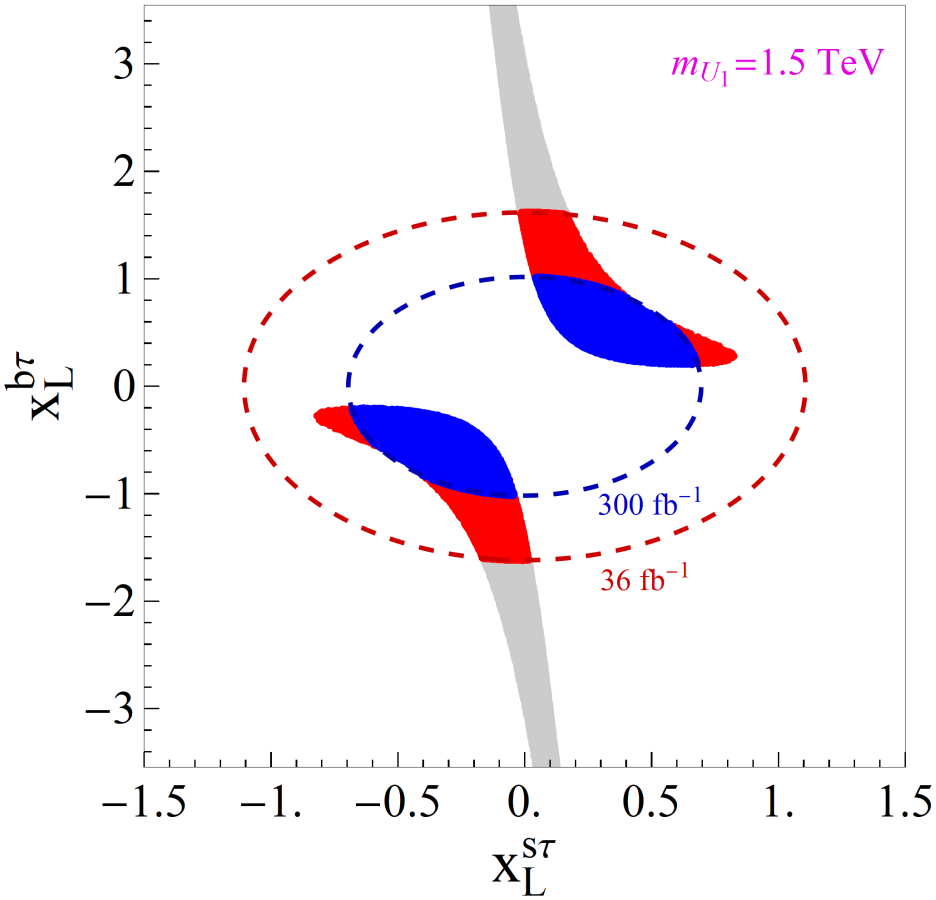




[Angelescu, Becirevic, Faroughy, **OS**. '18]

[see also Faroughy et al. '15]

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



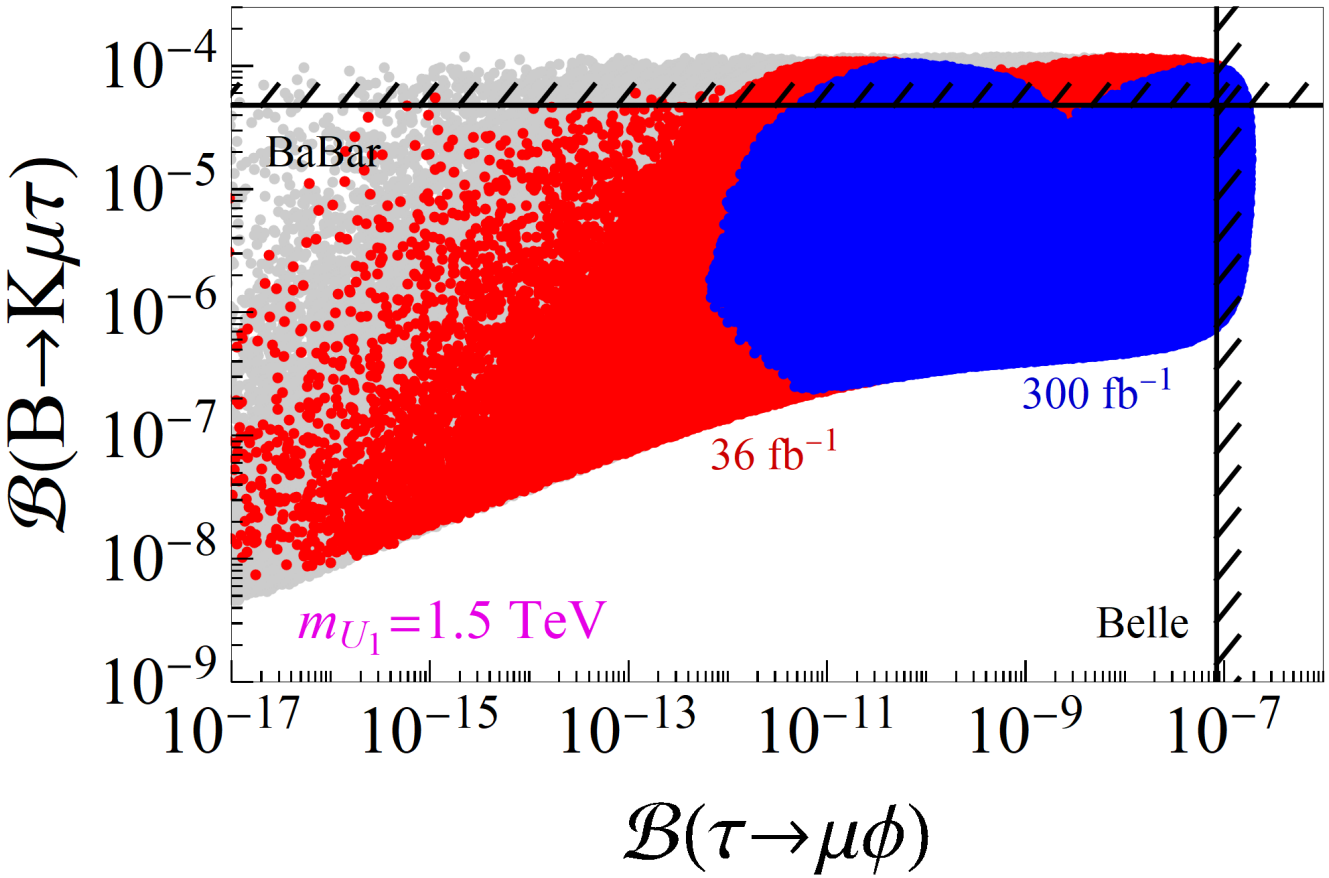
$R_{D^{(*)}}$ depends on:

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

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

$\Rightarrow$ 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: $\mathcal{B}(B \to K\mu\tau) \gtrsim \text{few} \times 10^{-7}$

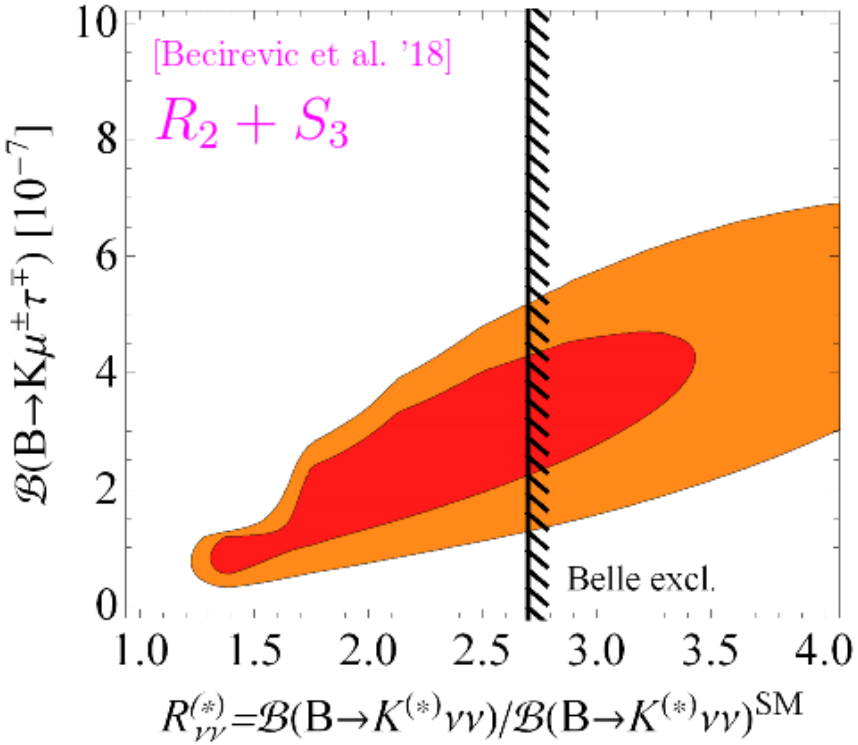


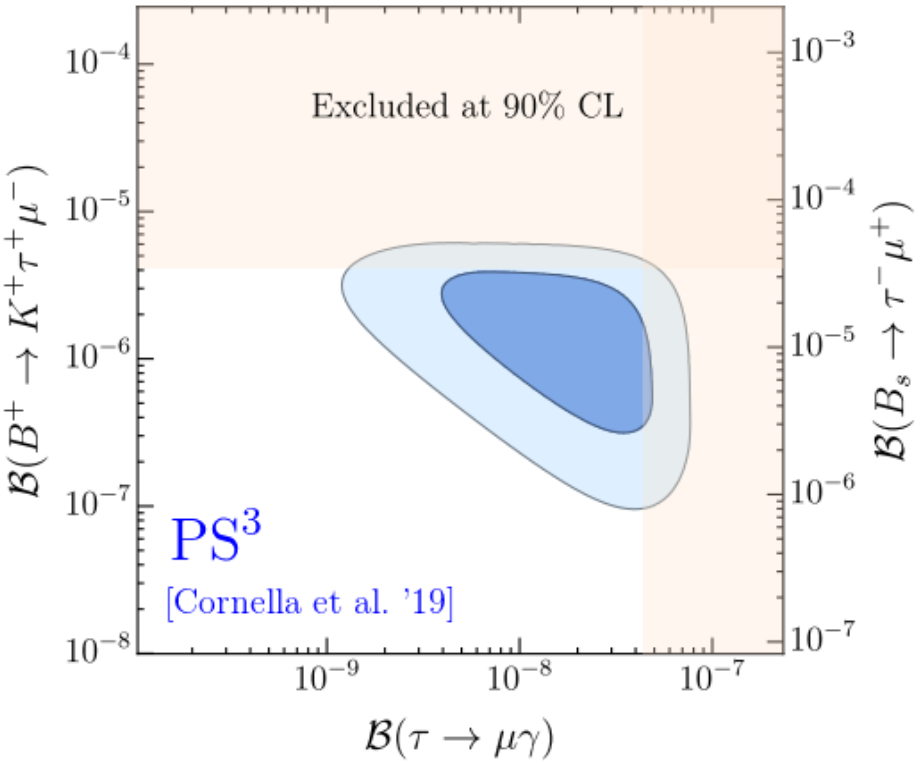
- BaBar: $\mathcal{B}(B \to K\mu\tau) < 4.8 \times 10^{-5}$. Can we do better?

- 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 [Guadagnoli et al. '14]





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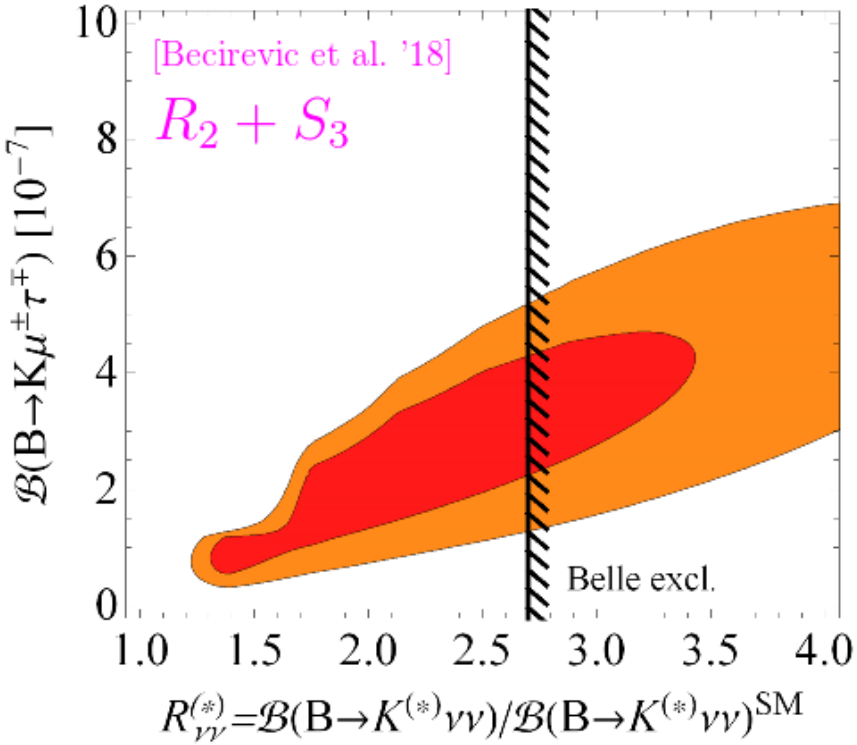
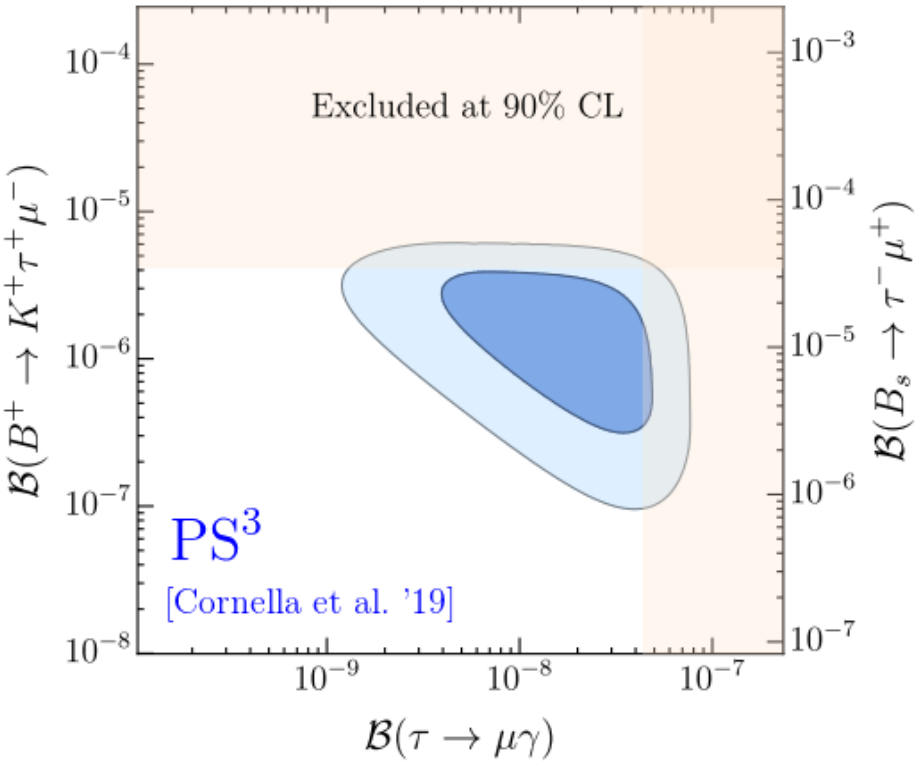




i) If purely $(V-A)\times(V-A)$:

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

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]

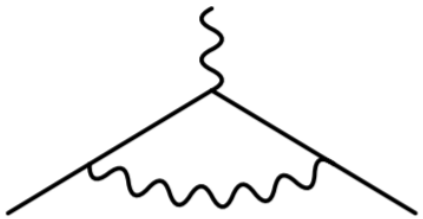
Final remarks: What about $(g-2)_\ell$?

[Cornella, Paradisi, **OS**. 1911.06279]

$(g-2)_\ell$ as a probe of new physics

- Long-standing discrepancy [$\approx 3.6\,\sigma$] in $(g-2)_\mu$:

$$\boxed{\begin{aligned} a_\mu^{\rm exp} &= 116592089(63)\times 10^{-11} \\ a_\mu^{\rm SM} &= 116591820(36)\times 10^{-11} \end{aligned}}$$



[Brookhaven, '06]
[Keshavarzi et al., '18], [Davier et al. '19]

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

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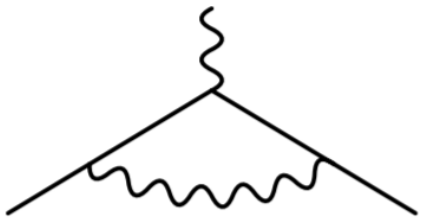

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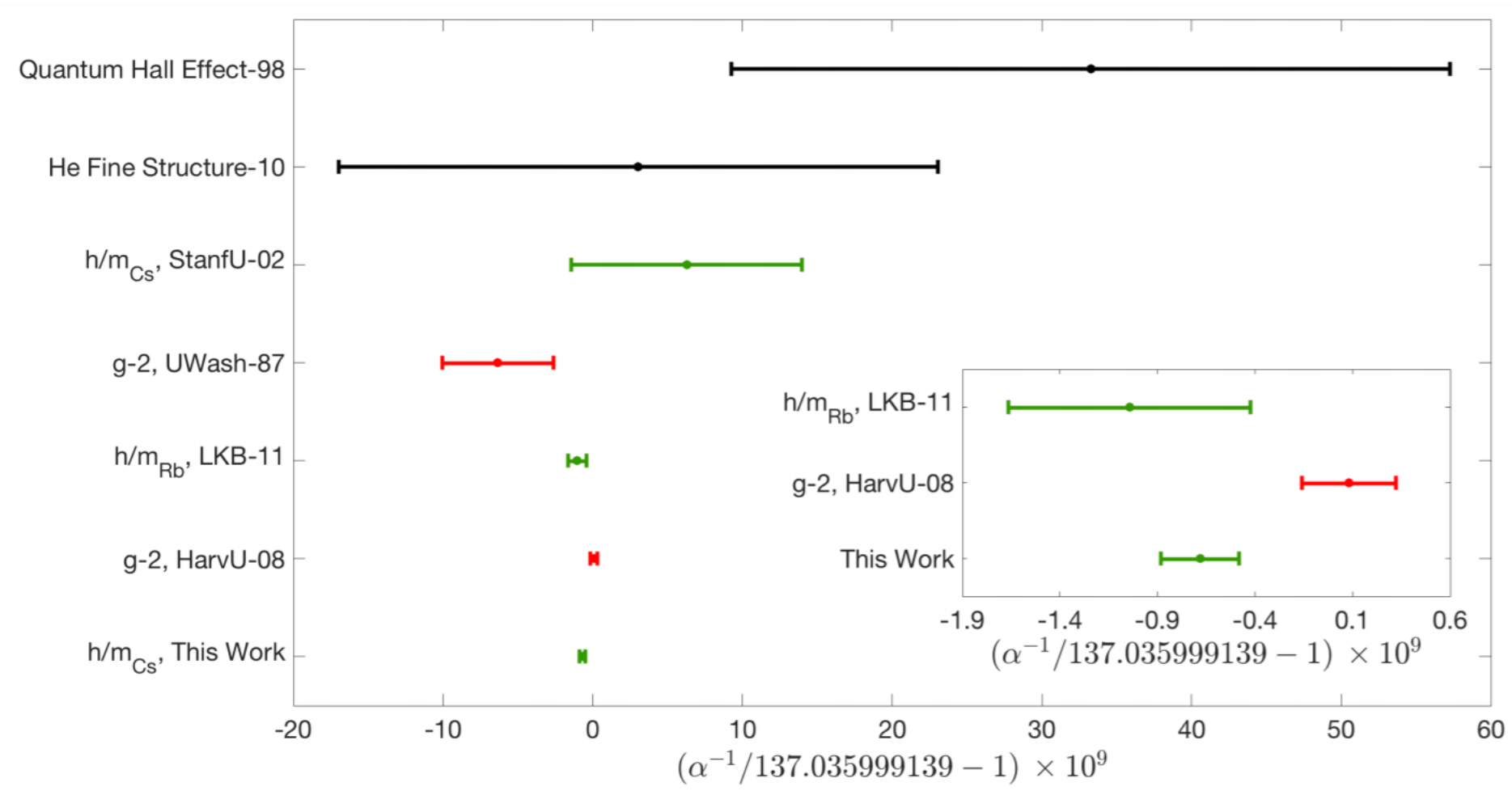
- New determination of α [Cs. '18] shows a $[2.4\sigma]$ discrepancy in $(g-2)_e$:

$$a_e^{\rm exp} = 11596521807.3(2.8) \times 10^{-13}$$
$$a_e^{\rm SM} = 11596521816.1(2.3)_{\delta_\alpha}(0.2)_{\rm th} \times 10^{-13}$$

(with the opposite sign!)

$\Rightarrow$ 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]

- In a broad class of BSM models: [Giudice et al. '12]

$$\frac{\Delta a_\mu}{\Delta a_e} = \left(\frac{m_\mu}{m_e}\right)^2 \qquad \text{(naive scaling)}$$

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$$\boxed{\Delta a_\mu^{\rm exp} = (2.7 \pm 0.7) \times 10^{-9}} \qquad \Rightarrow \qquad \Delta a_e^{\rm naive} = (7 \pm 2) \times 10^{-14}$$

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- There exist scenarios that violate the "naive scaling".

$\Rightarrow$ They can lead to large contributions to LFV or LFU breaking.

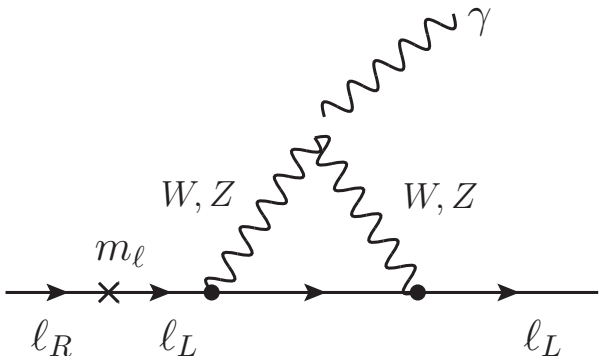
$\Rightarrow$ Example: light pseudoscalar with $a\gamma\gamma$ and $a\bar{\ell}\gamma_5\ell'$ couplings.

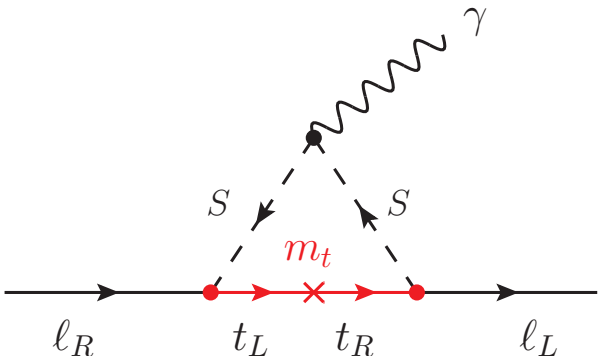
[Cornella, Paradisi, **OS**. '19]

see also [Davoudiasl '18], [Crivellin et al. '18], [Bauer et al. '19]

What about LQs?

- 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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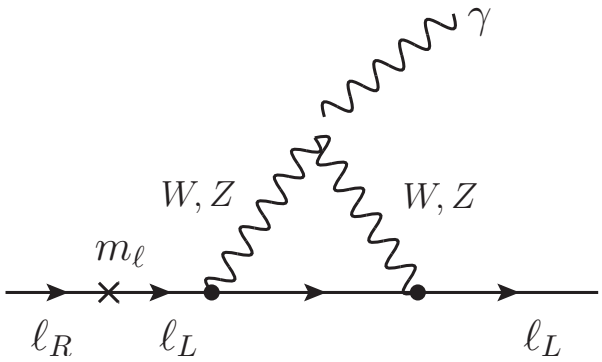

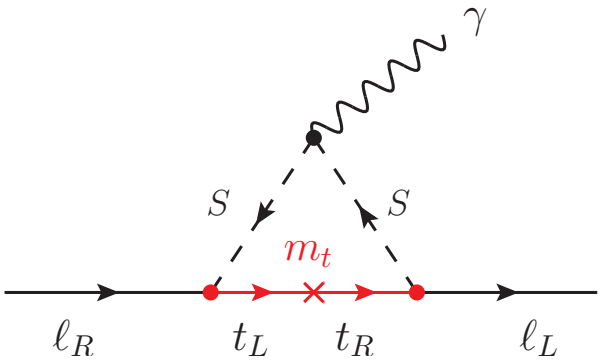

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- Explanation of **both** Δa_e and Δa_μ would imply too large $\mathcal{B}(\mu \to e\gamma)$:

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

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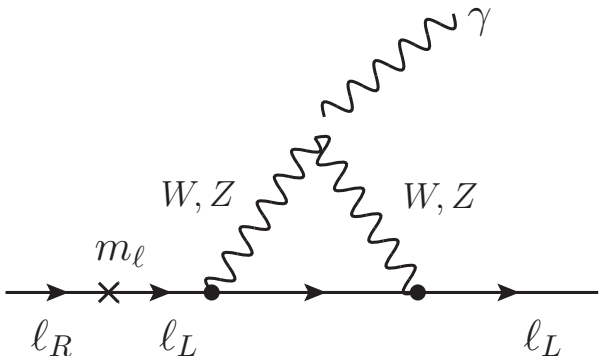

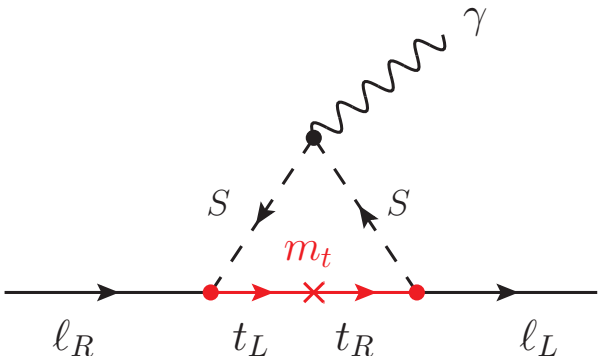

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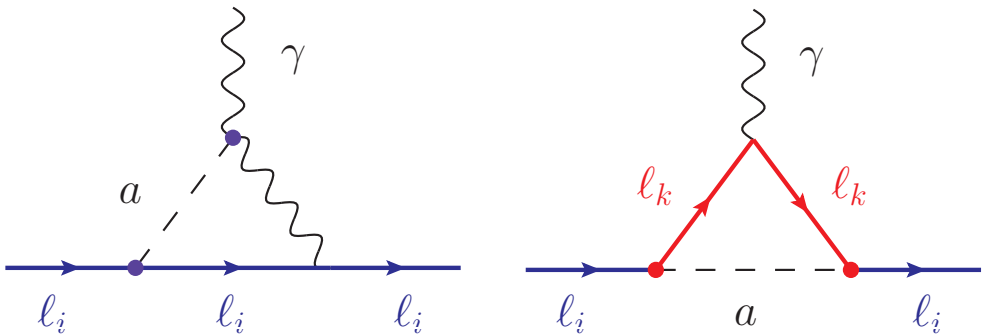
- Nevertheless, difficult to reconcile Δa_μ with B-anomalies...

Perhaps via LQ mixing? See [Dorsner, Fajfer, **OS**. '19]

Light pseudoscalars for $(g-2)_e$ and $(g-2)_\mu$

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



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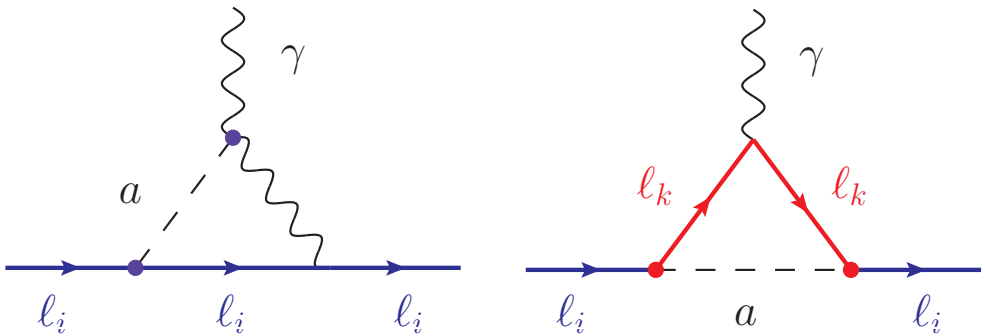

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- Barr-Zee diagram (left) can account for $(g-2)_\mu$: [Marciano et al. '16]

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

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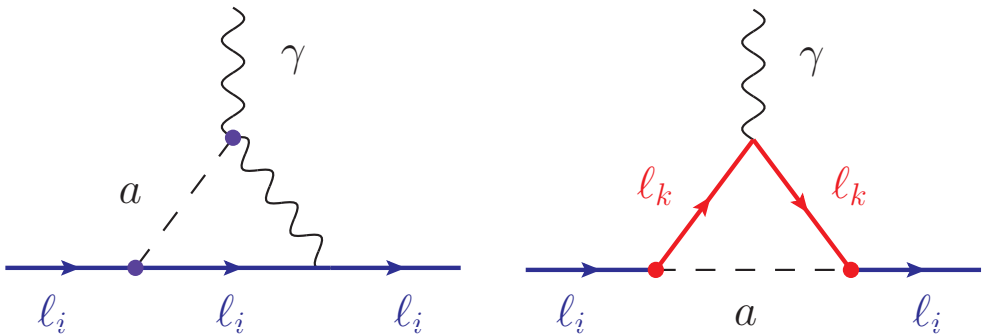

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$$(\Delta a_\mu)_{\rm LFC} \propto \frac{m_\mu^2}{\Lambda^2}\, a_{\mu\mu}^{\ell}\, a_{\gamma\gamma}\, \log\frac{\Lambda}{m_a} + \ldots$$

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

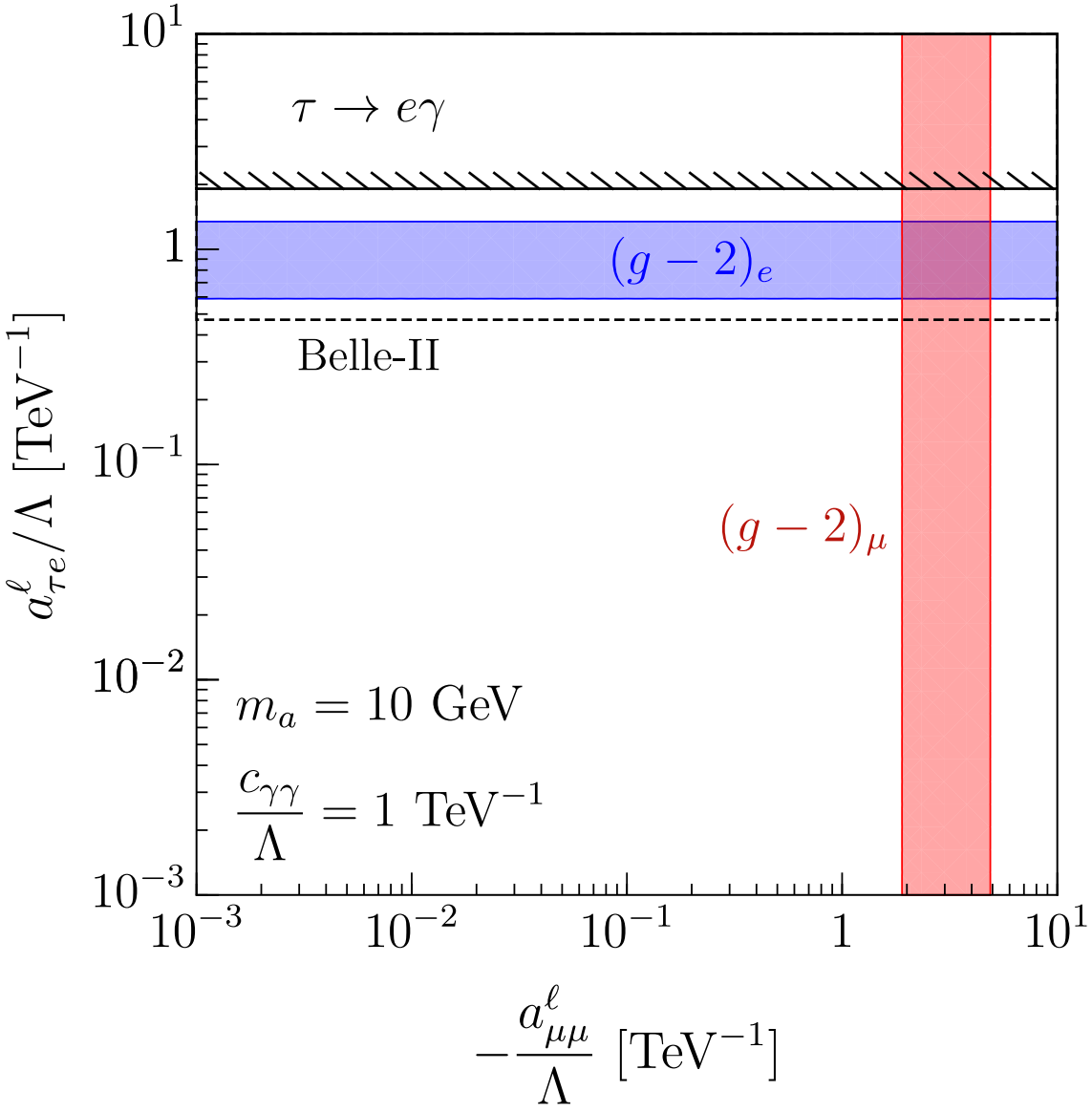
$$(\Delta a_e)_{\rm LFV} \propto \frac{m_\tau m_e}{\Lambda^2}\,|a_{e\tau}^{\ell}|^2$$

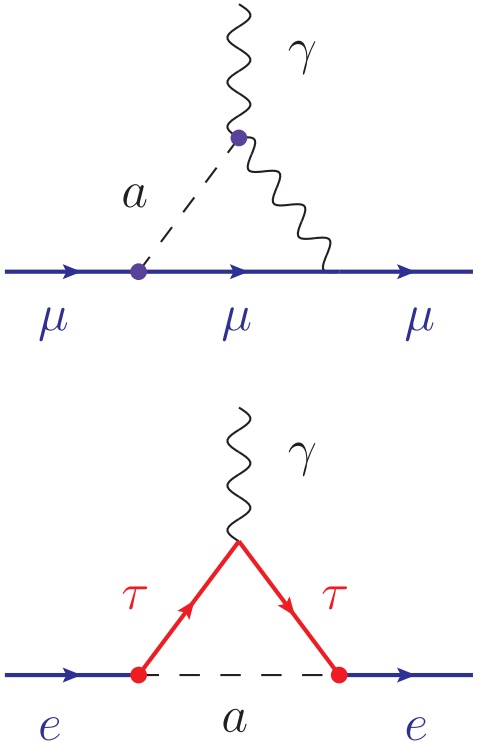
$\Rightarrow$ Both anomalies can be explained with reasonable couplings.

Predictions for Belle-II

[Cornella, Paradisi, **OS**. '19]

See also [Bauer et al. '19]



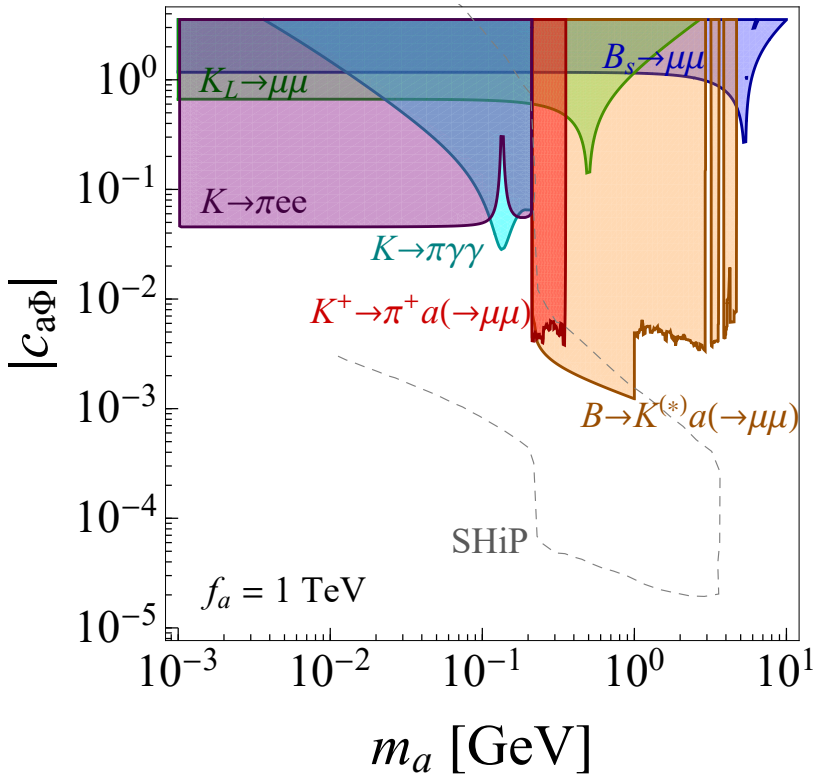


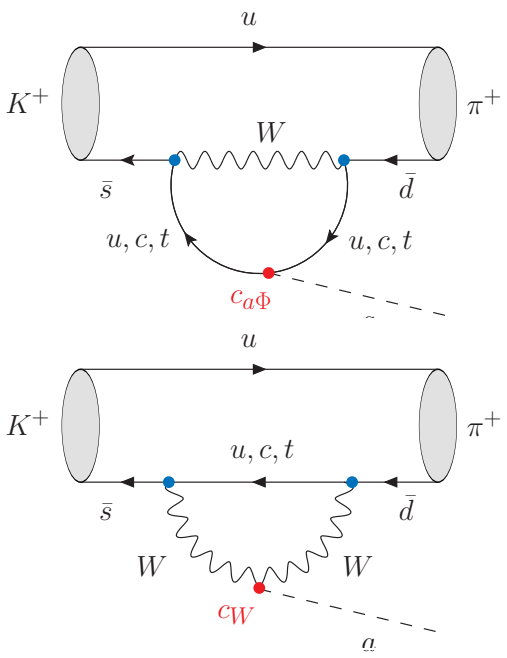
$\Rightarrow \mathcal{B}(\tau \to e\gamma) \approx 10^{-9}$ to be tested at Belle-II!

[Kuo et al. '18]

Rare decays as probes of light new physics

[Gavela, Houtz, Quilez, del Rey, **OS**. '19]





see also [Izaguirre et al. '16]

- $K \to \pi\nu\bar{\nu}$ and $B \to K^{(*)}\nu\bar{\nu}$ can be useful constraints.
- Novel signatures: displaced vertices in $B \to K^{(*)} a(\to \mu\mu)$. Useful results from LHCb already (orange regions)! [LHCb, '15, '16].

Summary and perspectives

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

  Needs 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 a pronounced 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

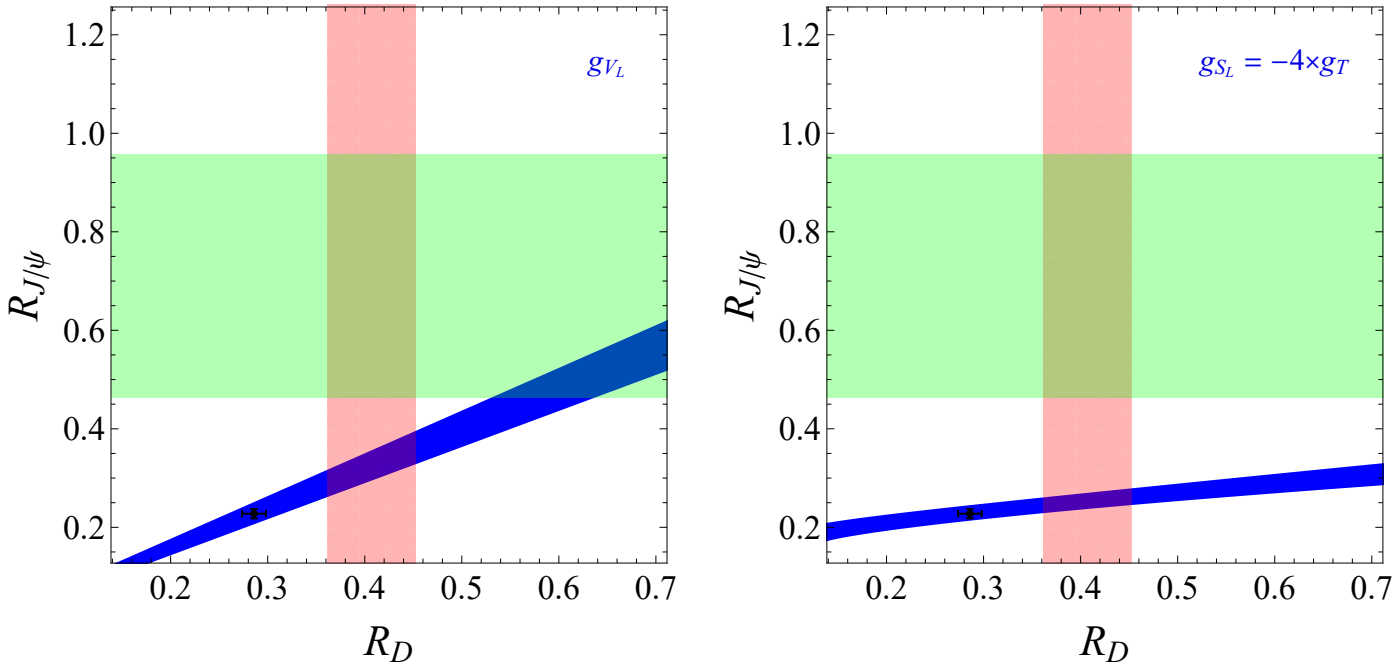
LHCb confirmed tendency in: [LHCb, '17]

$$R^{\rm exp}_{J/\Psi} = \frac{\mathcal{B}(B_c \to J/\Psi \tau \bar{\nu})}{\mathcal{B}(B_c \to J/\Psi \ell \bar{\nu})} = 0.71(17)(18)$$

$\Rightarrow$ Larger than SM estimates $R^{\rm SM}_{J/\Psi} \approx 0.22 - 0.28$; large exp/th errors.

$\Rightarrow$ Useful information to distinguish among NP scenarios:

[Melic, Becirevic, Leljak, OS. to appear]



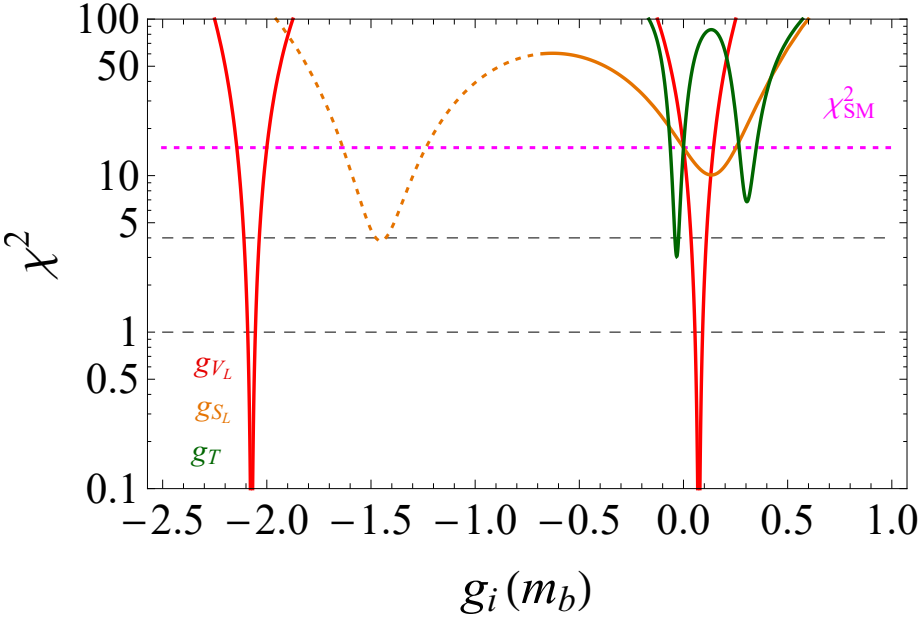
More exp. data and LQCD results are more than welcome here!

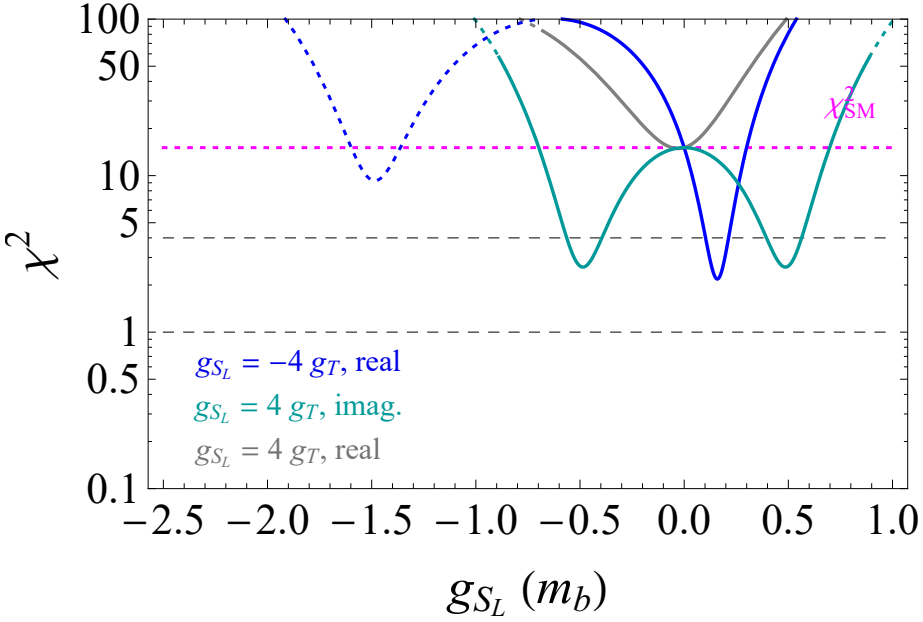
See [HPQCD, 1611.01987] for preliminary LQCD results for $V(q^2)$ and $A_1(q^2)$.

[Feruglio, Paradisi, OS. 1806.10155]

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

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

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

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

- In mass-eigenstates basis

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

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

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

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

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

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

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

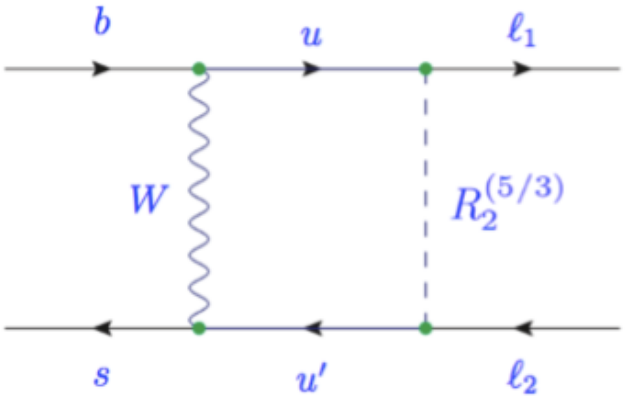
$R_2 = (3, 2, 7/6)$

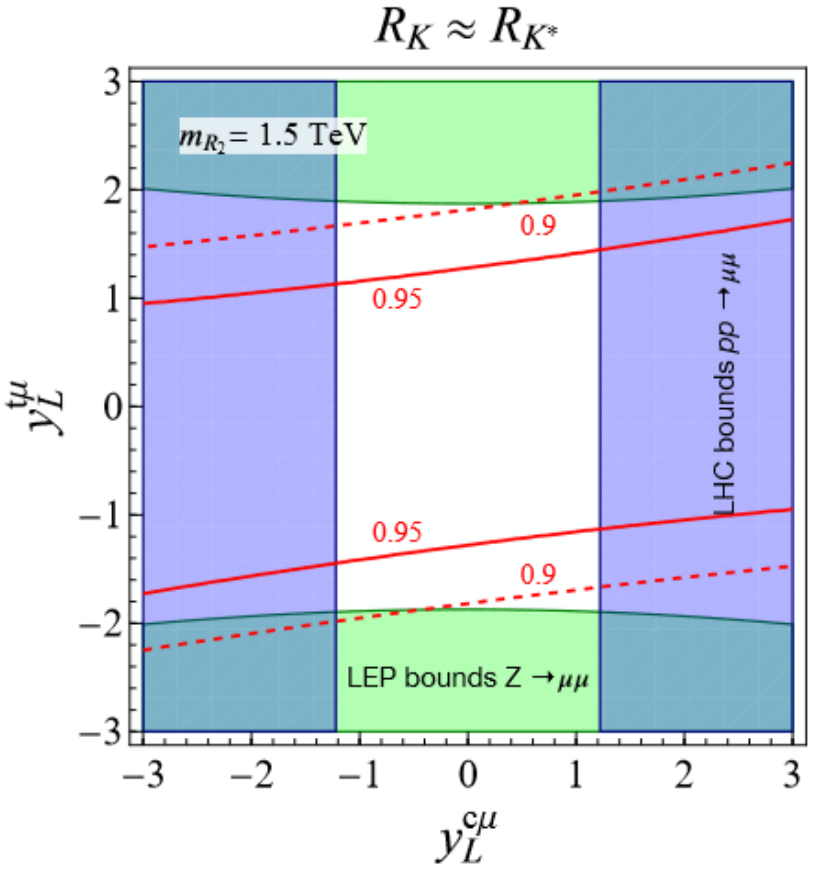
$$\mathcal{L}_{R_2} = y_R^{ij}\,\overline{Q}_i \ell_{R\,j}\,R_2 - \boxed{y_L^{ij}\,\overline{u}_{R\,i} R_2 i\tau_2 L_j} + \text{h.c.}$$

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

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

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





Update of [Becirevic, **OS**. ′17]

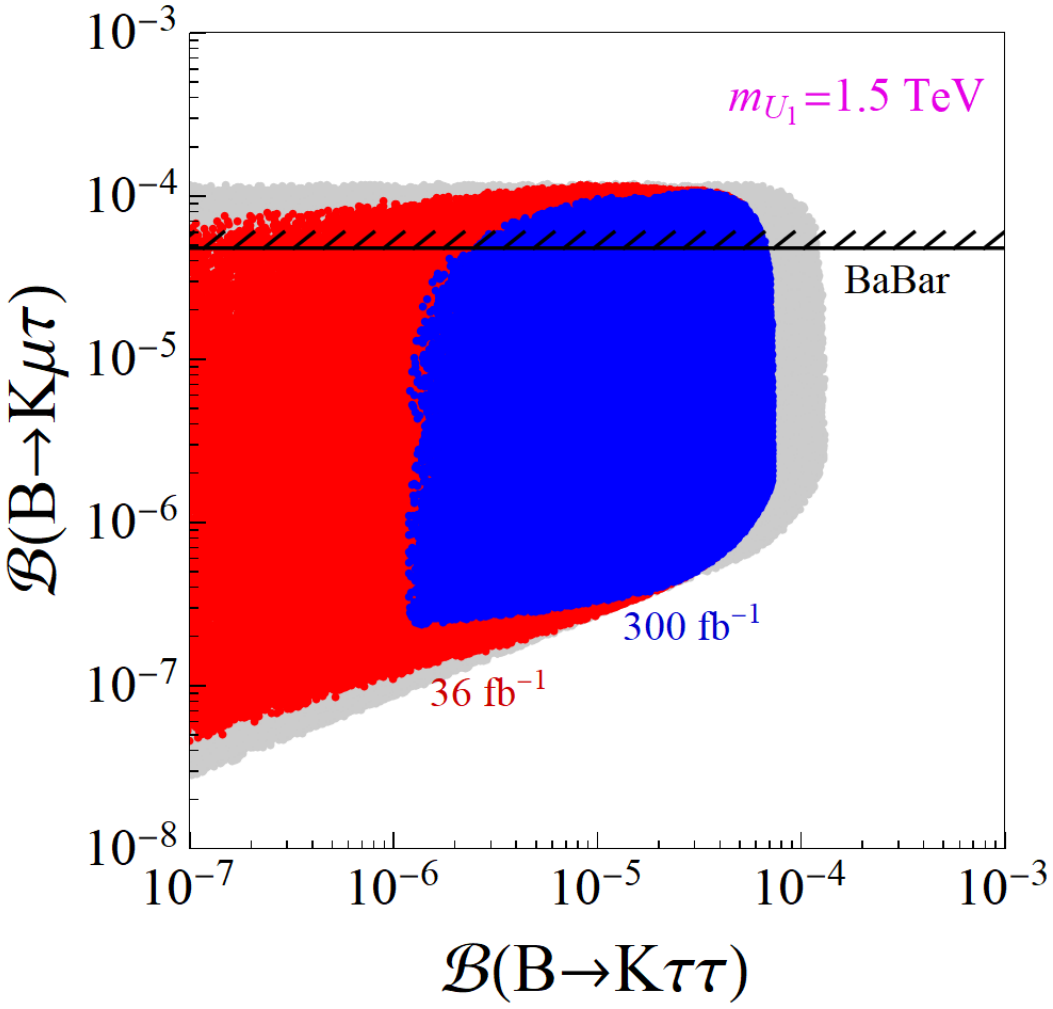
Limits on LQ pair-production

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

Decays	LQs	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\rm int}$ / 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]



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

$\Rightarrow$ Can it be tested experimentally?

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

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

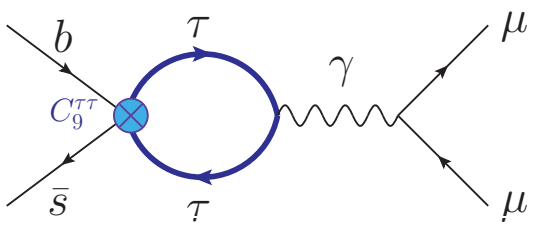
- Existing direct limits:

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

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

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

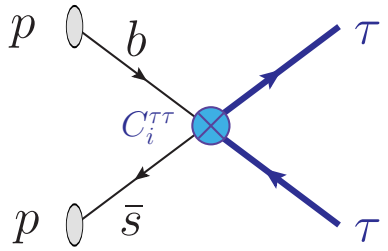
- New idea: deformation of $B \to K\mu\mu$ q^2-spectrum



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

[M. König, LHCb Implications '19]

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



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

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

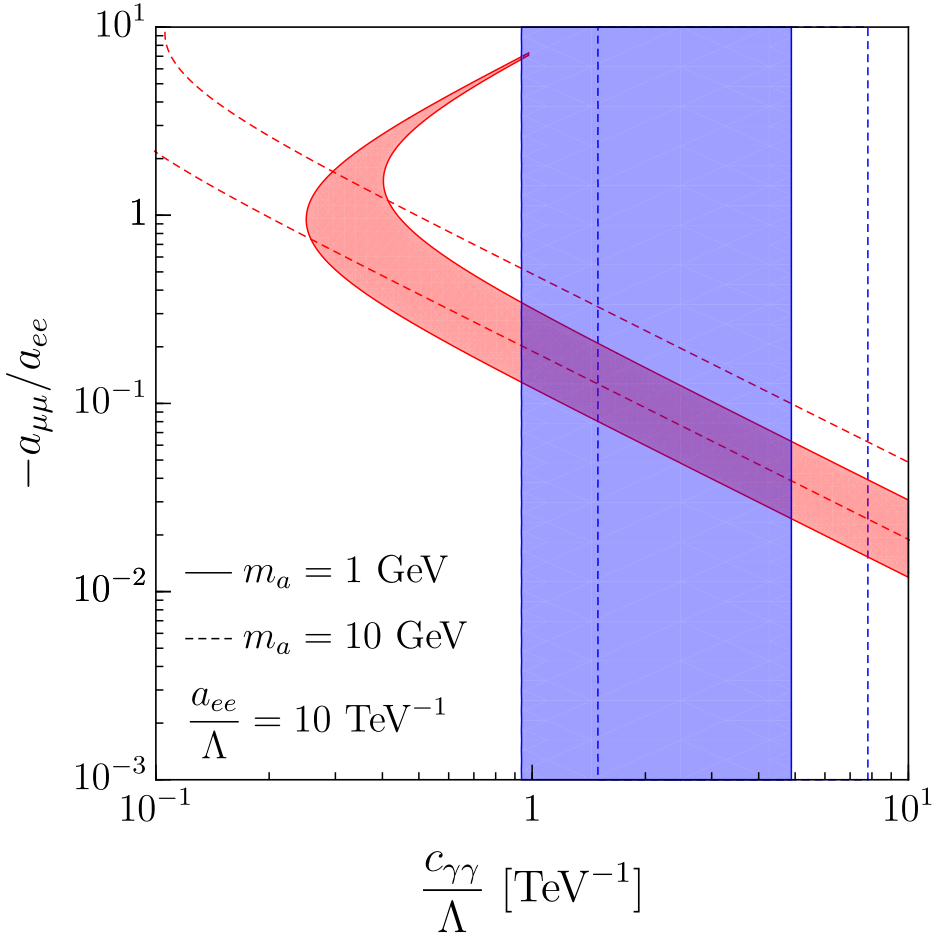
[Angelescu, Faroughy, **OS**. To appear]

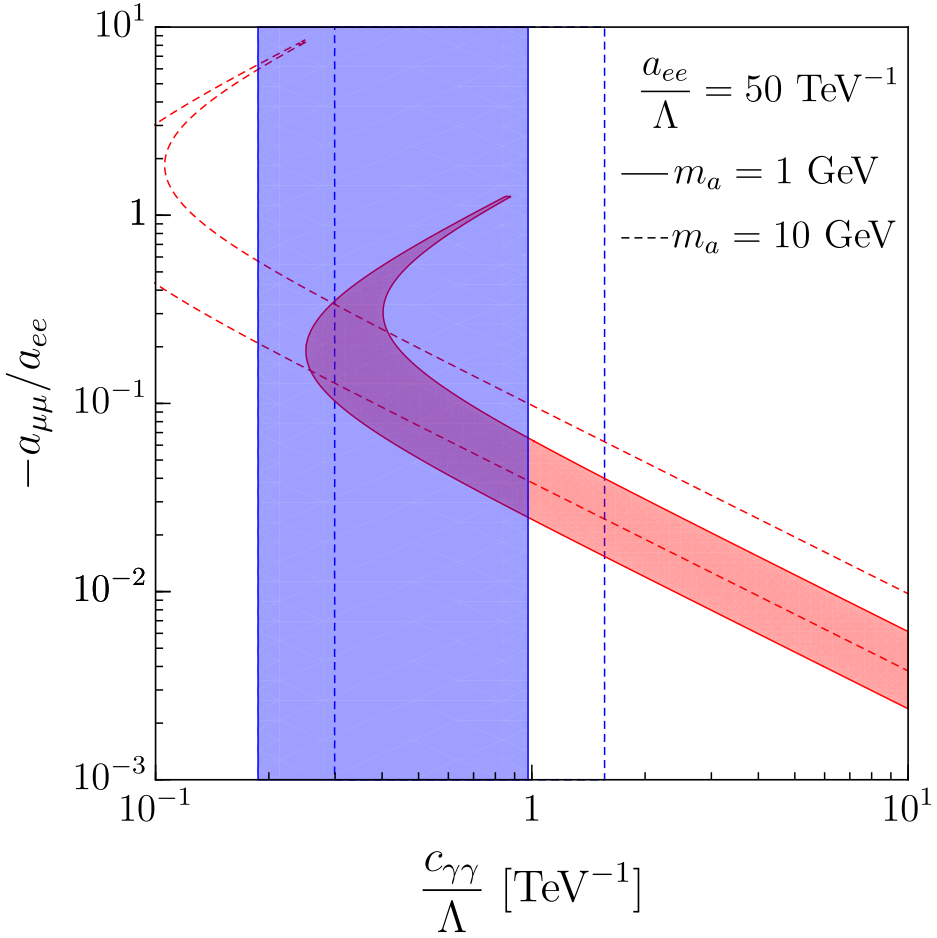
but more model dependent (EFT validity?)

Take-home: Different approaches are complementary!

$(g-2)_e$ and $(g-2)_\mu$ from flavor-conserving ALP couplings

[Cornella, Paradisi, **OS**. '19]





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)!