B-physics anomalies: a road to New Physics?

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IJCLab (Orsay)

In collaboration with **A. Angelescu, D. Becirevic, D. Faroughy** *and* **F. Jaffredo** [2103.12504]

FNAL, 23/04/21

Lepton Flavor Universality (LFU) — Motivation

- **Well-tested** property of the SM **gauge sector**, which is broken by Yukawas:

$$g_V \equiv g_V^\ell$$

[LEP, τ-decays]

- Several **discrepancies** have been observed in ***b*-hadron** decays:

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

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

See also:

R_{pK}

$R_{J/\Psi}$

[LHCb, B-factories]

- **If confirmed** with more data, they will indicate the existence of **New Physics** at the **O(TeV) scale**.

Outline

I. Introduction: Flavor in the SM and beyond

II. *B*-physics anomalies:

- Where do we stand?
- EFT interpretations
- From EFT to concrete models

III. Closing the leptoquark window

IV. Muon g-2: another LFU hint?

V. Summary

Flavor physics

- Gauge sector of the SM entirely **fixed by symmetry**:

  $\Rightarrow$ Only a handful of parameters.

  $\Rightarrow$ Theory renormalizable and verified at the loop-level.

- Flavor sector **loose**:

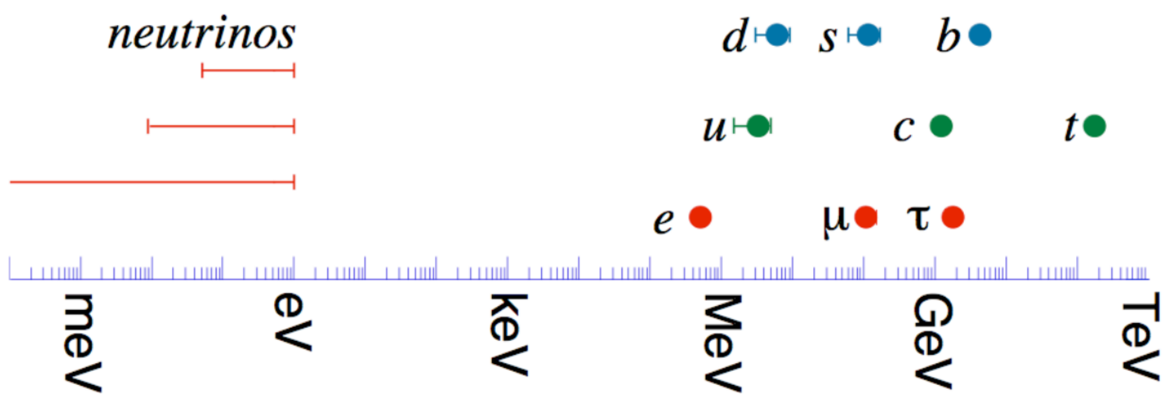
  $\Rightarrow$ 13 free parameters (masses and quark mixing) – fixed by data.

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

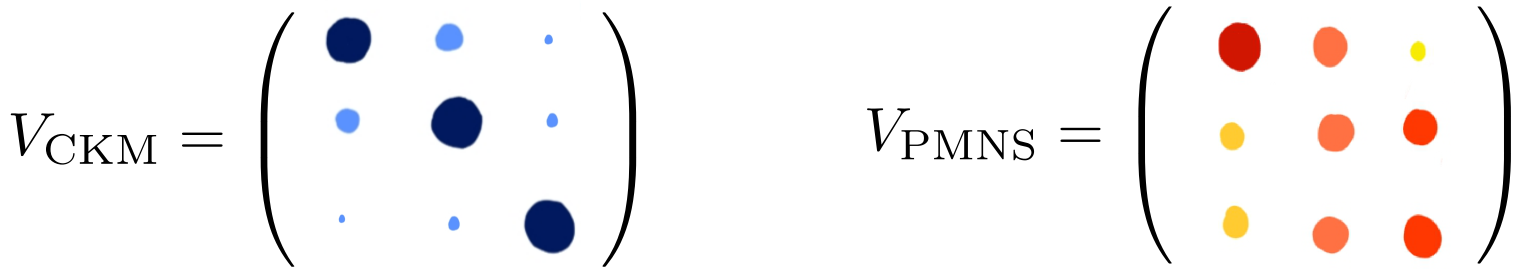
  $\Rightarrow$ These (many) parameters exhibit a hierarchical structure which we do not understand.

Origin of flavor?

- **Striking hierarchy** of fermion masses *[does not look accidental...]*



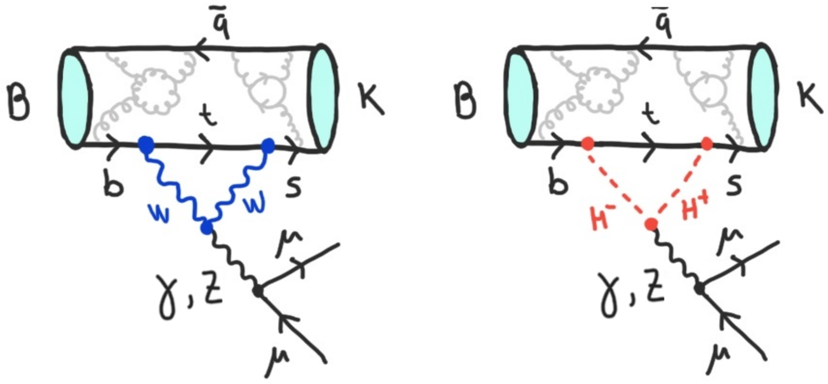
- Why **three** families? Why do **quarks** and **leptons** mix in **different ways**?



To identify symmetries beyond those present in the SM is one of the roles of **flavor physics**

Indirect Searches of New Physics

(i) **Search of deviations** w.r.t. the SM predictions:



$\Longrightarrow$ Possible thanks to recent progress in lattice QCD simulations

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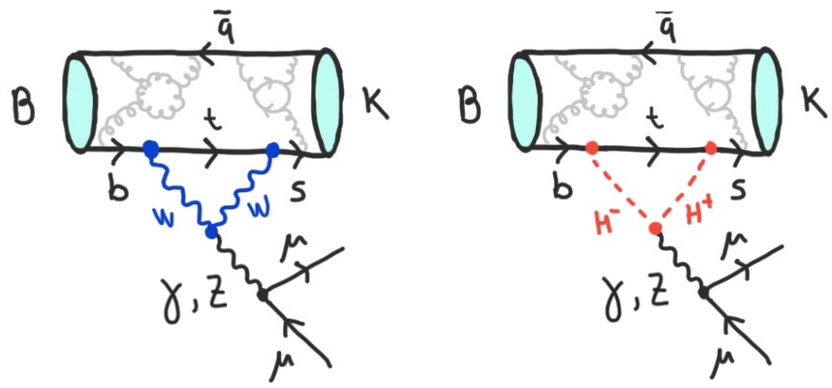

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(ii) **Search of processes forbidden** by (*accidental*) *symmetries* of the SM:

- Proton decay **(BNV)**
- $0\nu\beta\beta$ **(LNV)**
- Lepton Flavor Violation **(LFV)**

$\Longrightarrow$ Clean probes of New Physics!

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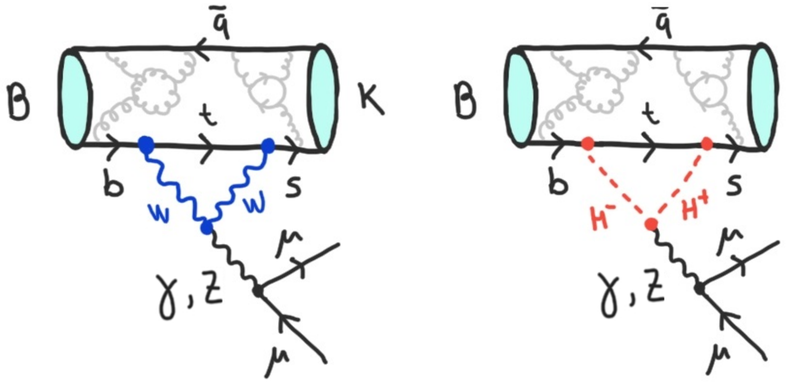

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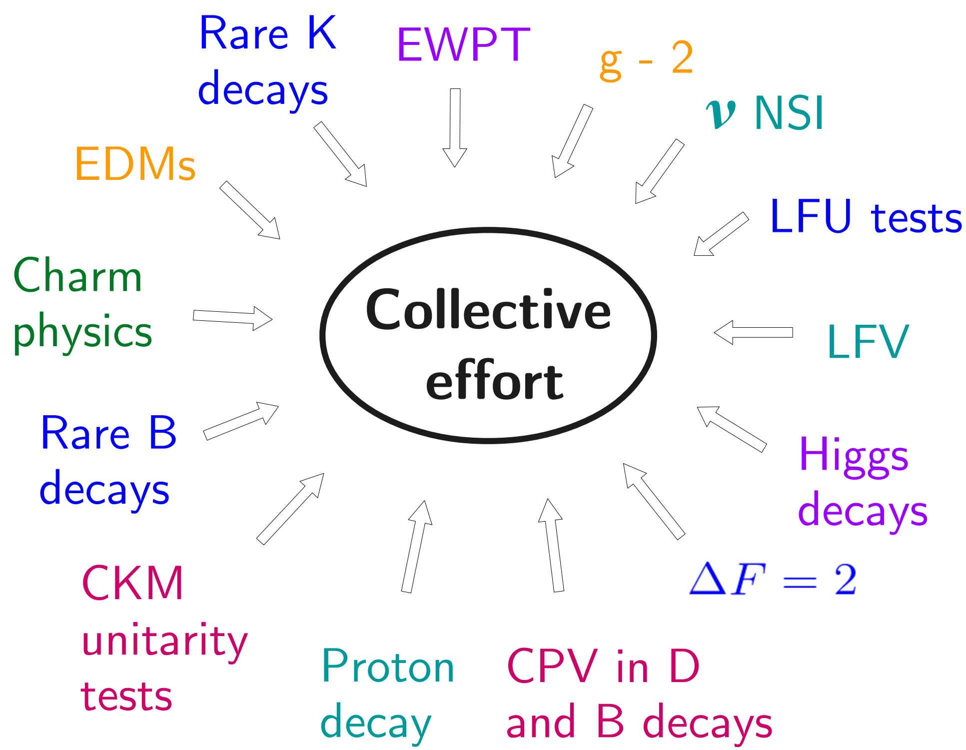


Indirect searches are **complementary** to the direct searches at the **LHC**.

They **can probe energy scales** that are **not directly accessible** at colliders – i.e. $C_i/\Lambda_{\rm NP}$.

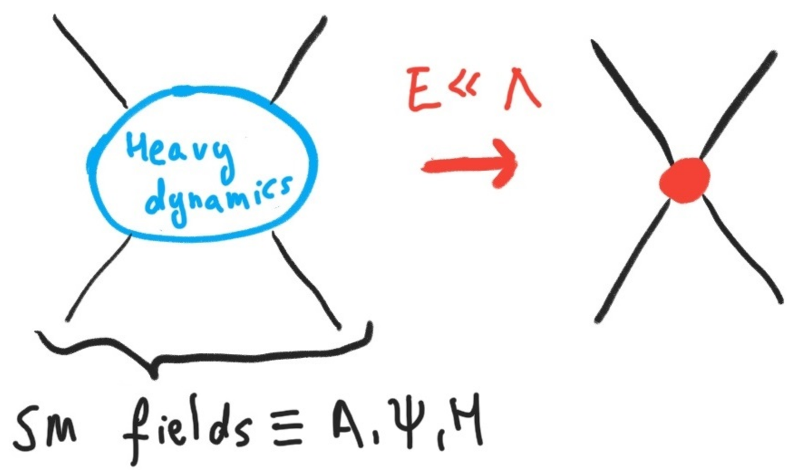
How do we do it?

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

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

Assumption: $E \ll \Lambda$

Most general description of new physics particles as long as there is not enough energy to produce them.



Lessons from Flavor Physics

PLB 192 (1987)

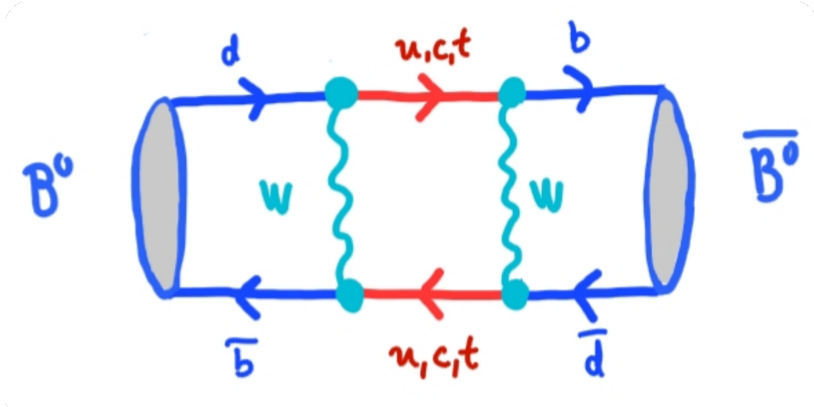
OBSERVATION OF B^0–$\bar{B}^0$ MIXING

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 Υ (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
$B^{1/2} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$ pion) decay constant
$m_b < 5$ GeV$/c^2$	b-quark mass
$\tau < 1.4 \times 10^{-12}$s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi–Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [a)]
$m_t > 50$ GeV$/c^2$	t quark mass

An example:



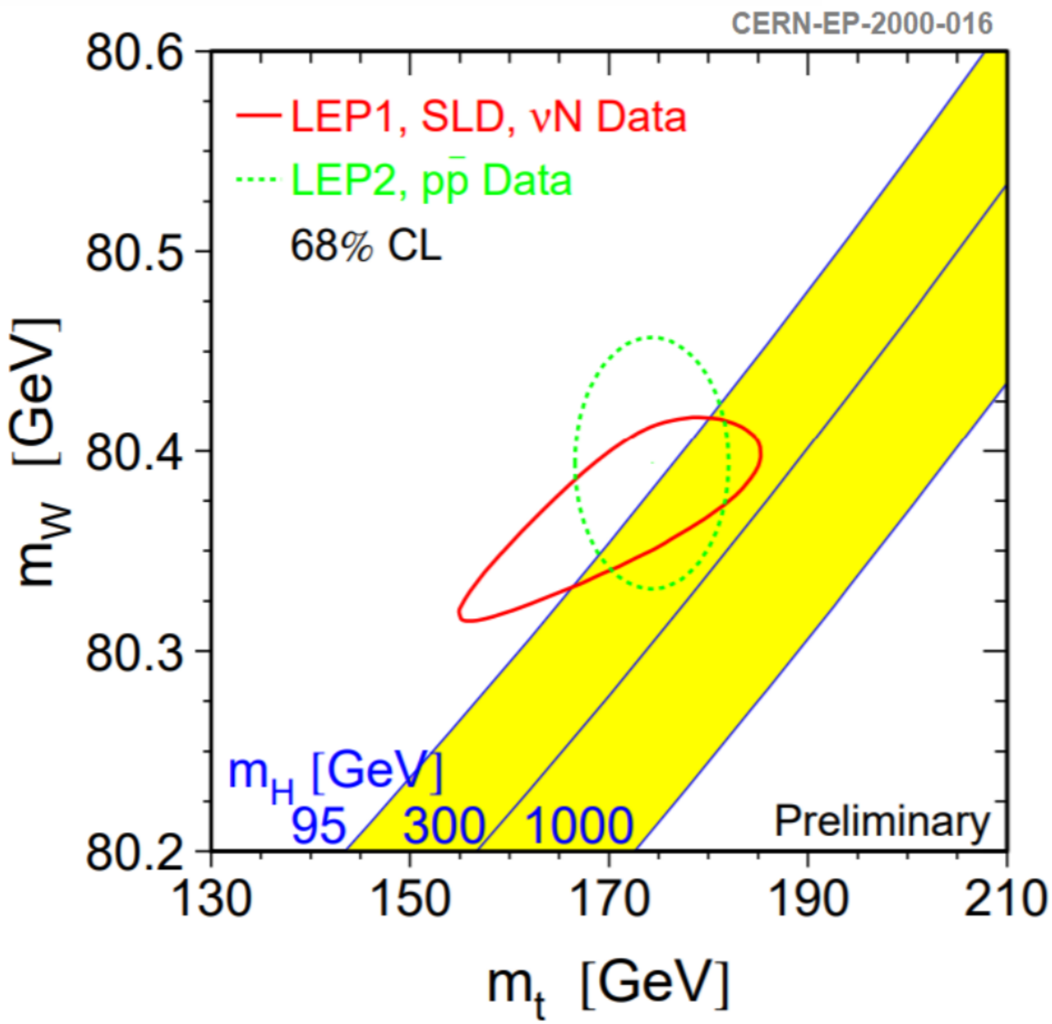
GIM mechanism:

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

[Grossman, Tanedo. TASI Lectures]

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!

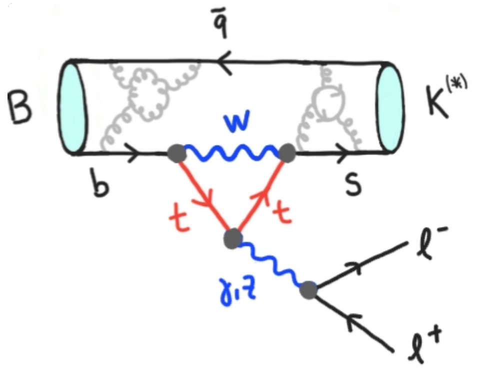
Combined effort: electroweak precision measurements (LEP) and searches in the **high-energy** frontier (Tevatron).

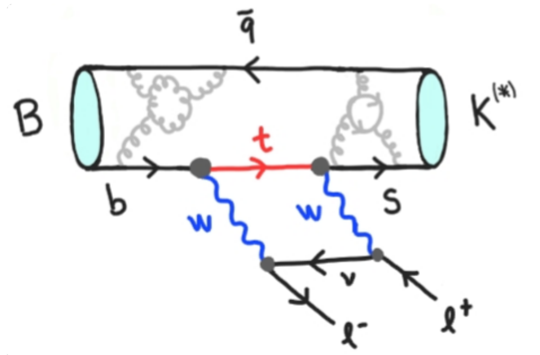


Lepton Flavor Universality

$B \to K^{(*)}\mu\mu$ decays in the SM

FCNC: loop-induced in the SM





QCD uncertainties are an **obstacle**...

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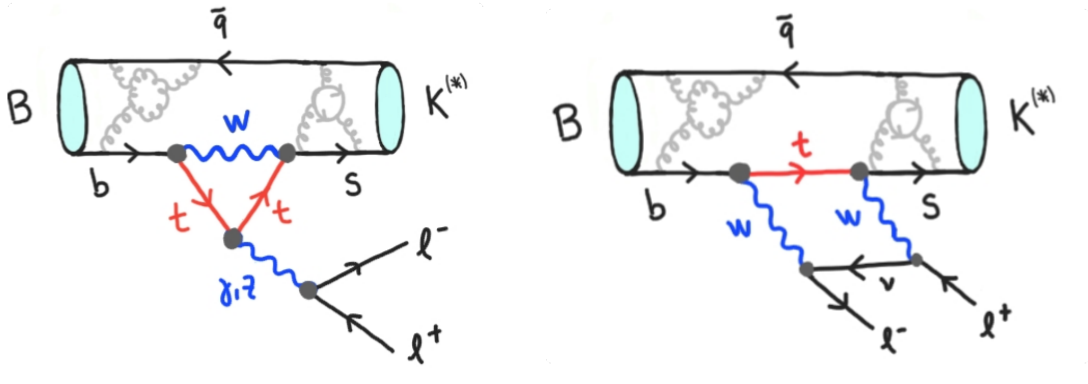

QCD uncertainties are an **obstacle**...

- **Form-factors:**

$$\langle K^{(*)}(k)|J_\mu|B(p)\rangle = \sum_a K_\mu^a \, F_a(q^2)$$

Kinematical factors

Form-factors
(to be determined, e.g. by **LQCD**)

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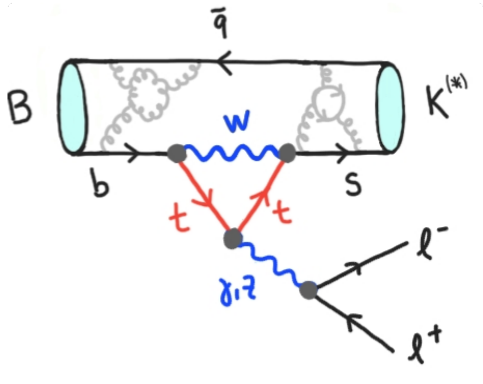

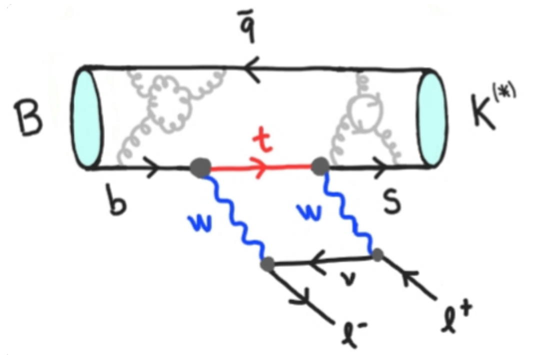

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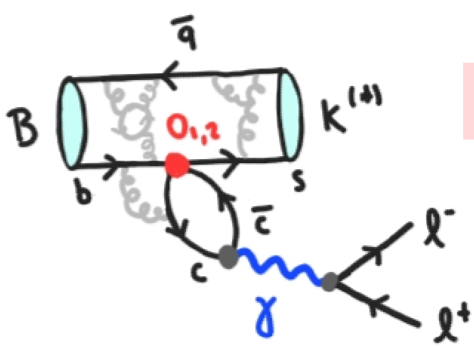

Hard to compute...

[Grinstein, Pirjol. '04]

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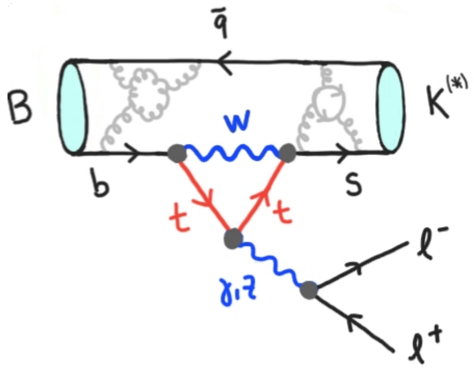

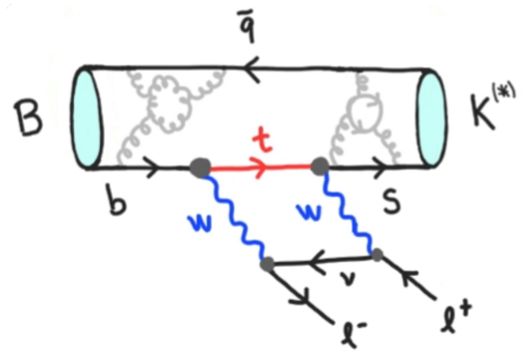

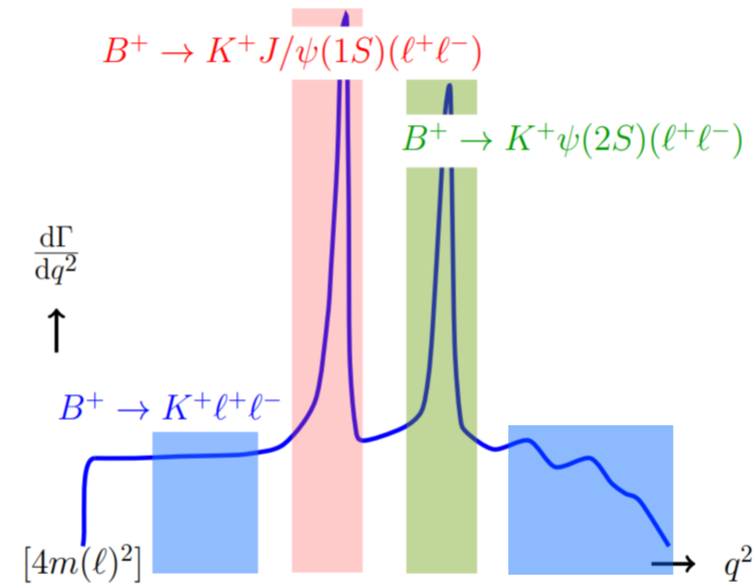

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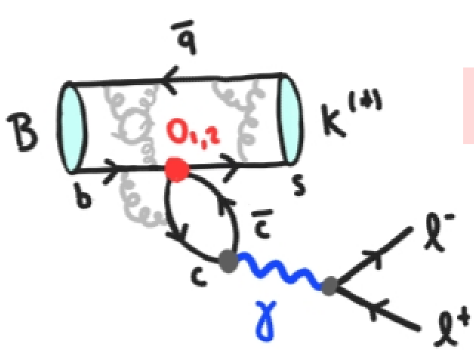

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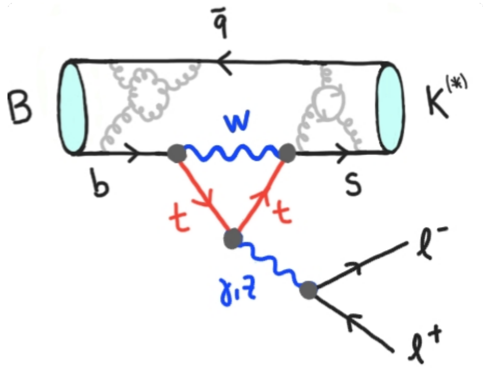

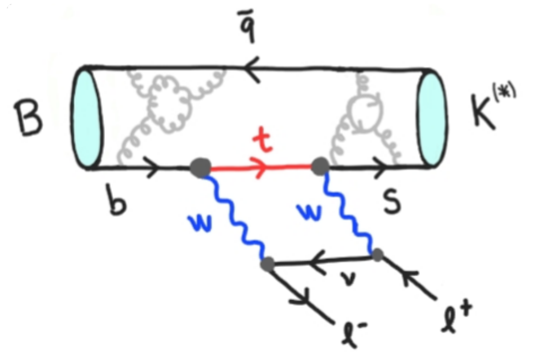

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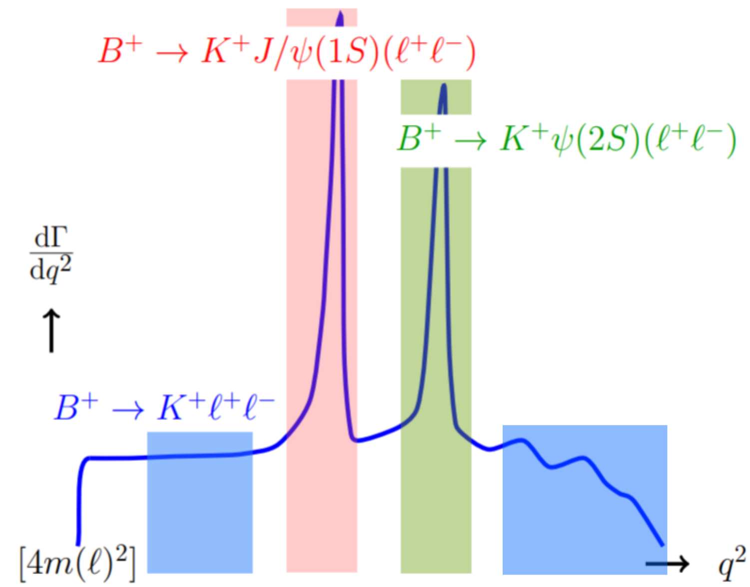

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- **Non-local contributions:**

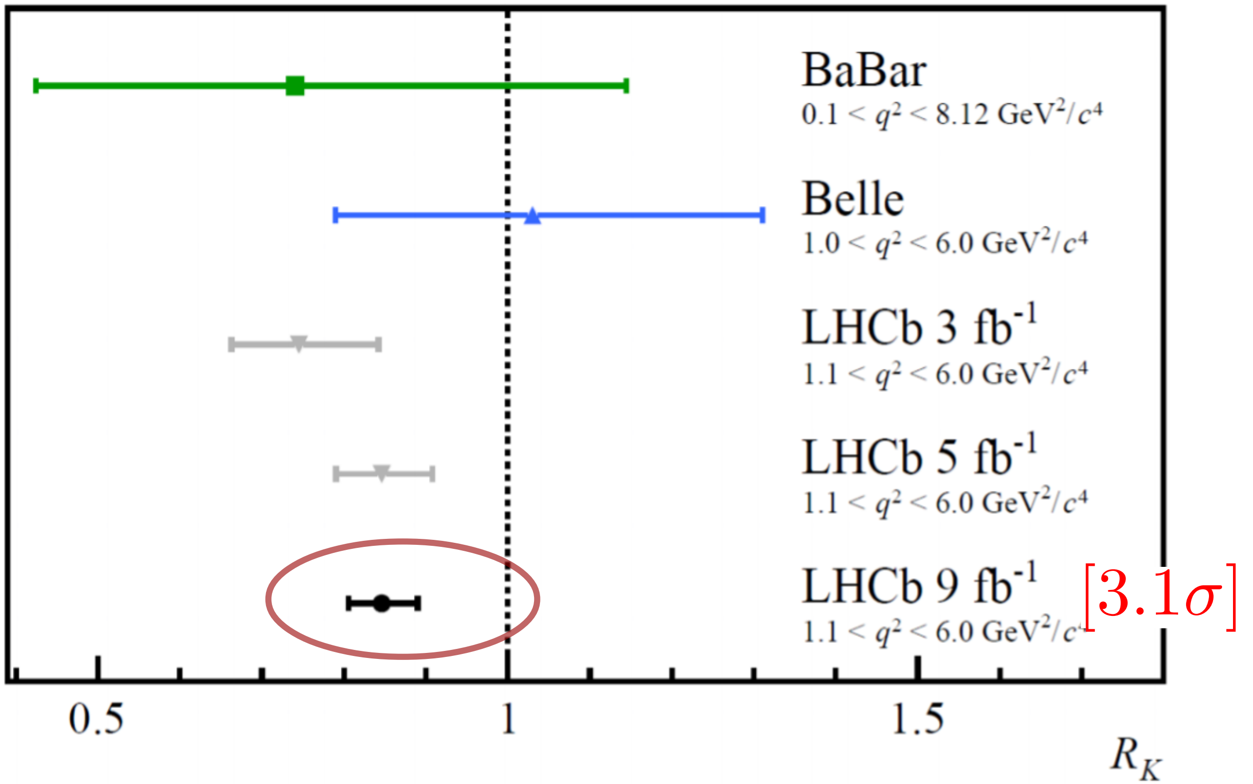
Hard to compute...

These **uncertainties cancel out** in **LFU** ratios!

[Grinstein, Pirjol. '04]

Recent LHCb results

$$R_K = \frac{\mathcal{B}(B \to K\mu\mu)}{\mathcal{B}(B \to Kee)}$$



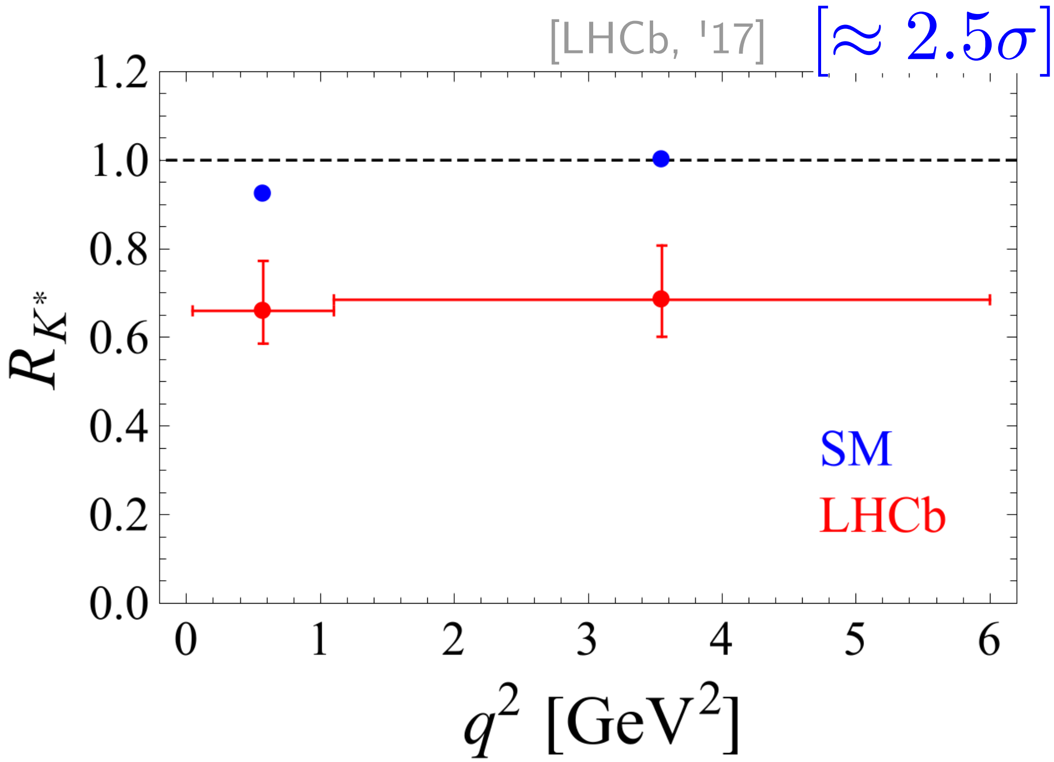
Theory (loop-induced):

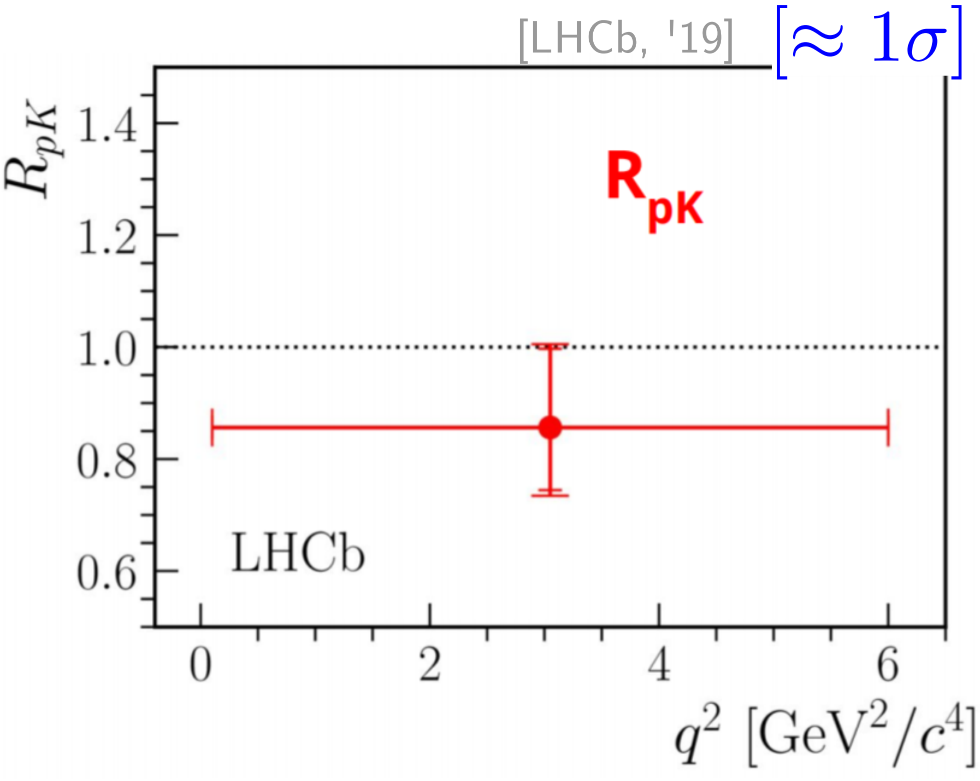
- Hadronic uncertainties cancel to a large extent.

  $\Rightarrow$ **Clean observable!** *[working below the narrow $c\bar{c}$ resonances]*

- QED corrections important, $R_K^{\mathrm{SM}} = 1.00(1)$ [Isidori et al. '20]

Other LFU measurements





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

$$R_{pK} = \frac{\mathcal{B}(\Lambda_b \to pK \mu\mu)}{\mathcal{B}(\Lambda_b \to pK ee)}$$

vs. $R_X^{\mathrm{SM}} \approx 1$

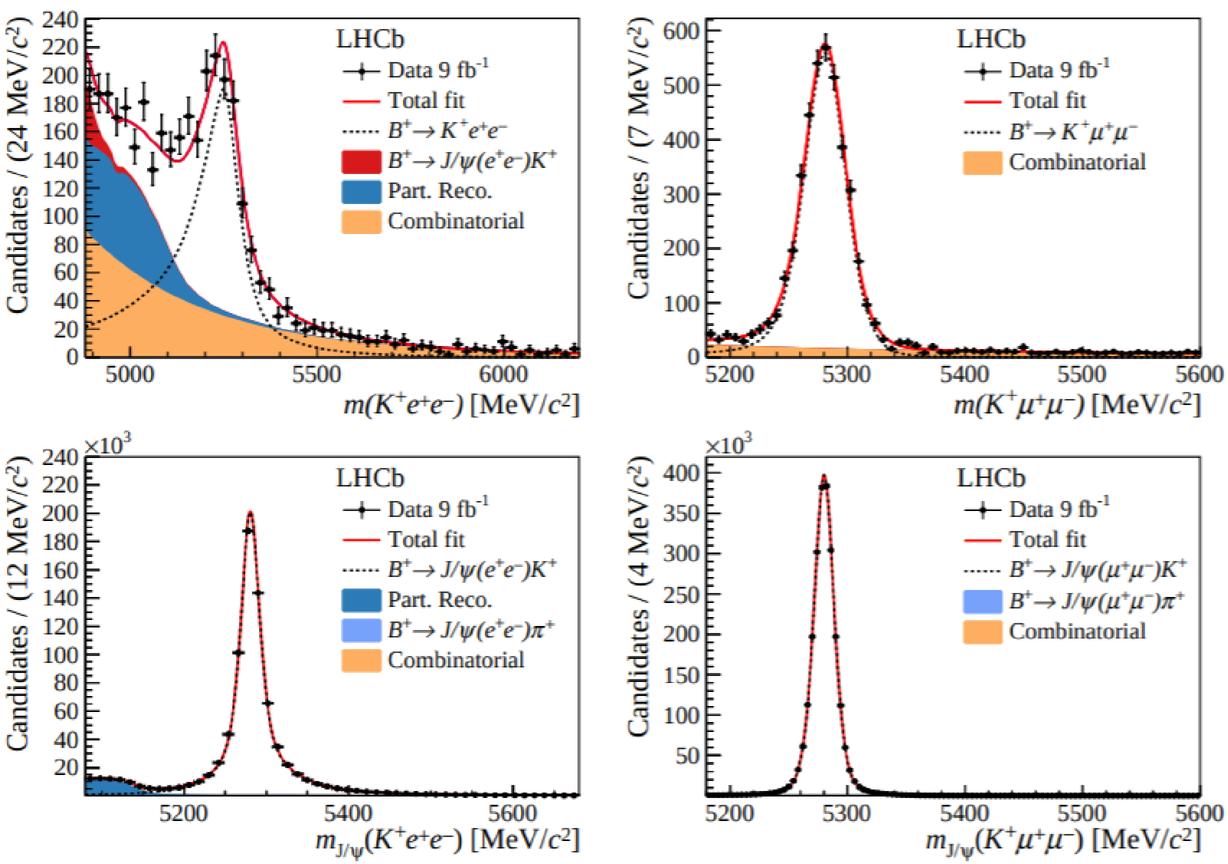
Coherent pattern of deviations!

Experimental strategy

[LHCb, 2103.11769]

Double ratio

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+ \mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+ e^-))}$$



Cross-check:

$$r_{J/\psi}^{\exp} = \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+ \mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+ e^-))}$$

$$= 0.98(2)$$

Further cross-checks

[LHCb, 2103.11769]

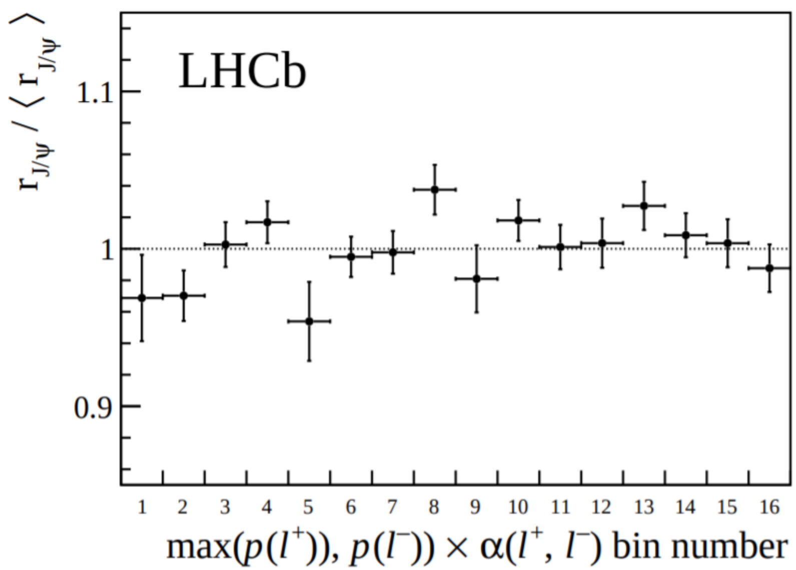
i) LFU at $\psi(2S)$:

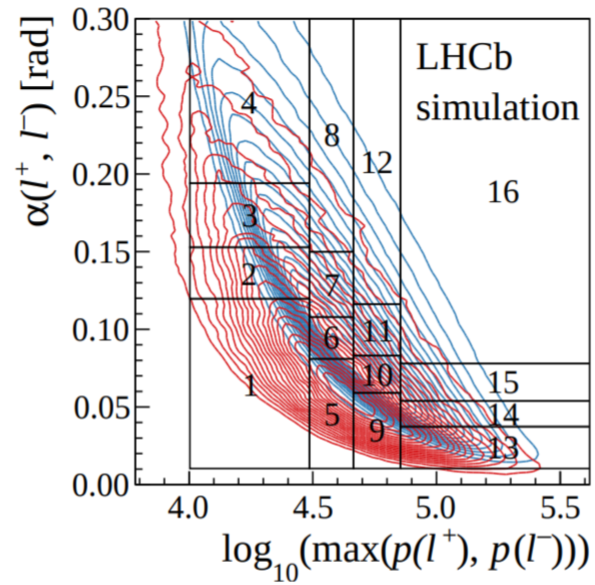
$$R^{\rm exp}_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(e^+e^-))}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$

$$= 0.997(11)$$

ii) Kinematical dependence:

$$r^{\rm exp}_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$





Belle-II will be **fundamental** to **confirm/refute** these results.

EFT interpretations

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

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

- **Semileptonic operators**:

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

$$\mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

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

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

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

[Buchmuller, Wyler. '85]

- **(Pseudo)scalar** operators are **tightly constrained** by

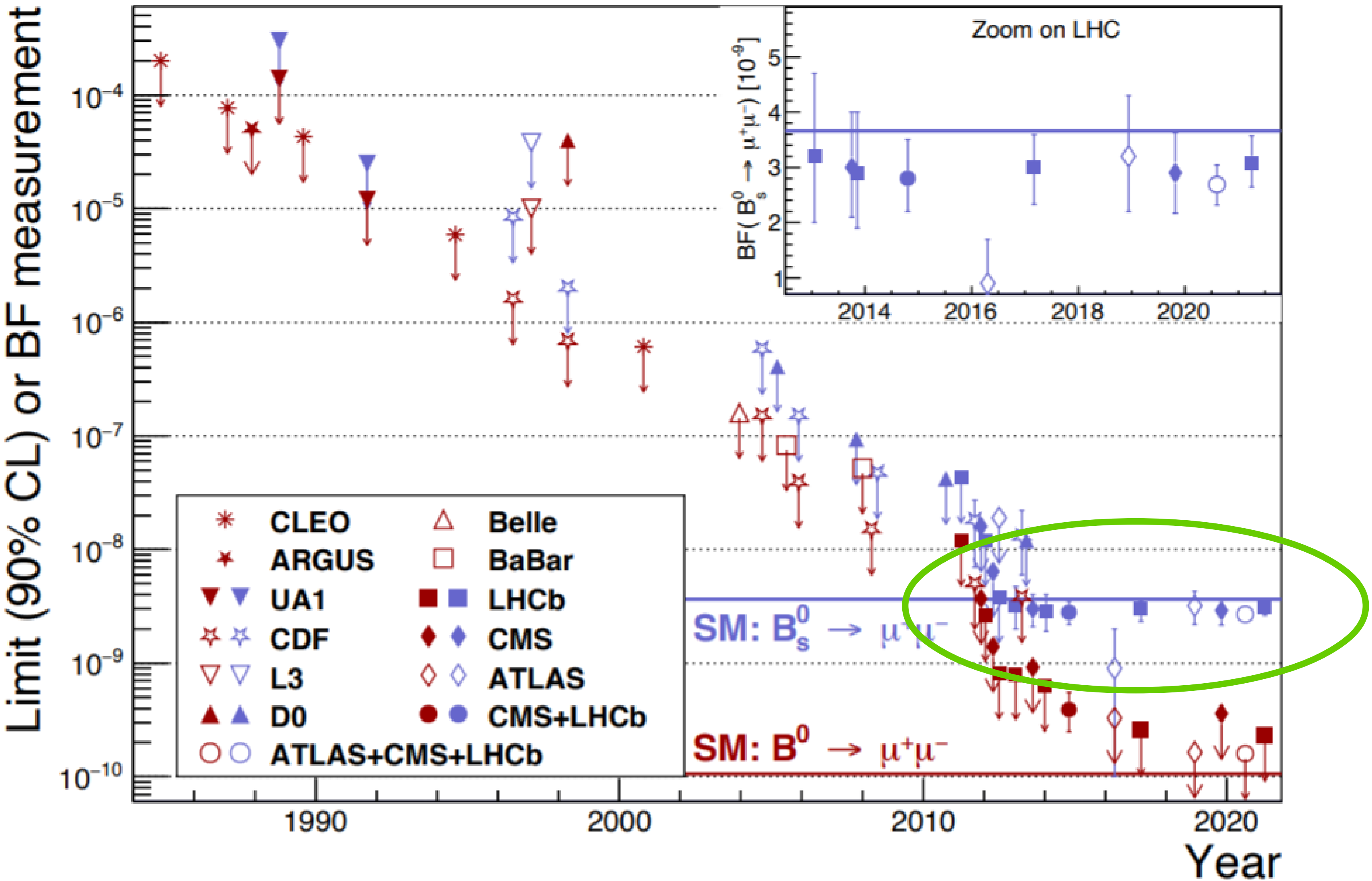
$$\overline{\mathcal{B}}(B_s \to \mu\mu)^{\text{exp}} = (2.85 \pm 0.22) \times 10^{-9}$$

[Our average, CMS, ATLAS, LHCb]

$$\overline{\mathcal{B}}(B_s \to \mu\mu)^{\text{SM}} = (3.66 \pm 0.14) \times 10^{-9}$$

[Beneke et al. '19]

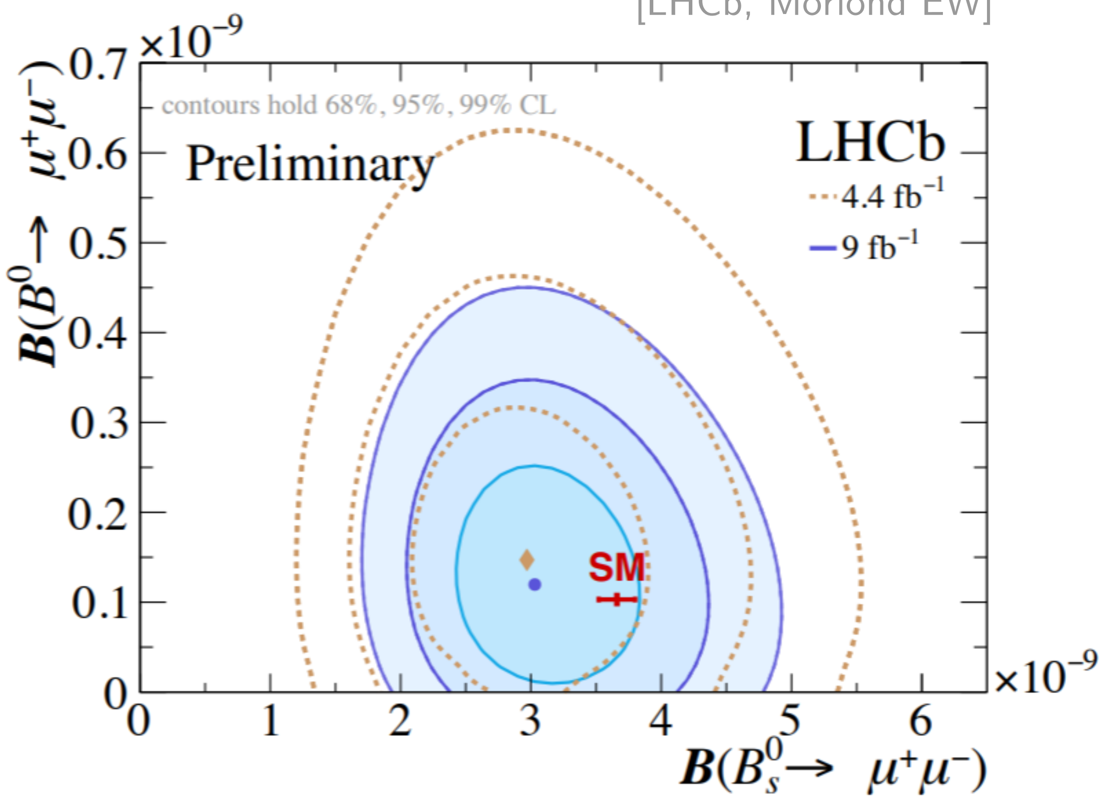
A long journey...



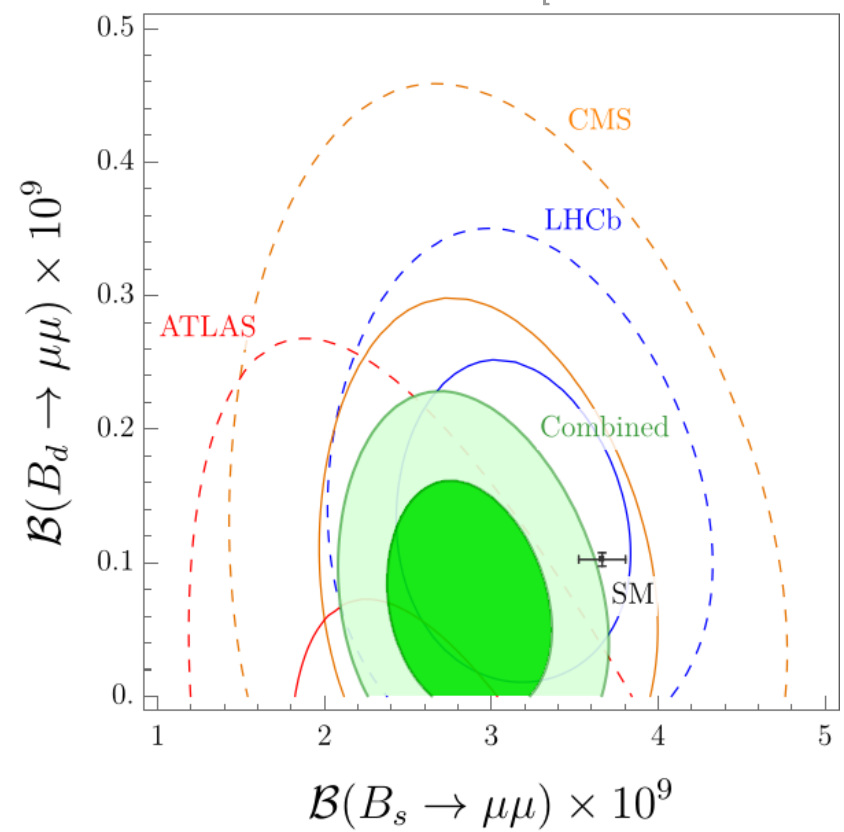
Latest LHCb results

[Angelescu, Becirevic, Faroughy, Jaffredo, **OS**. '21]

[LHCb, Moriond EW]



see also [Cornella et al. '21]



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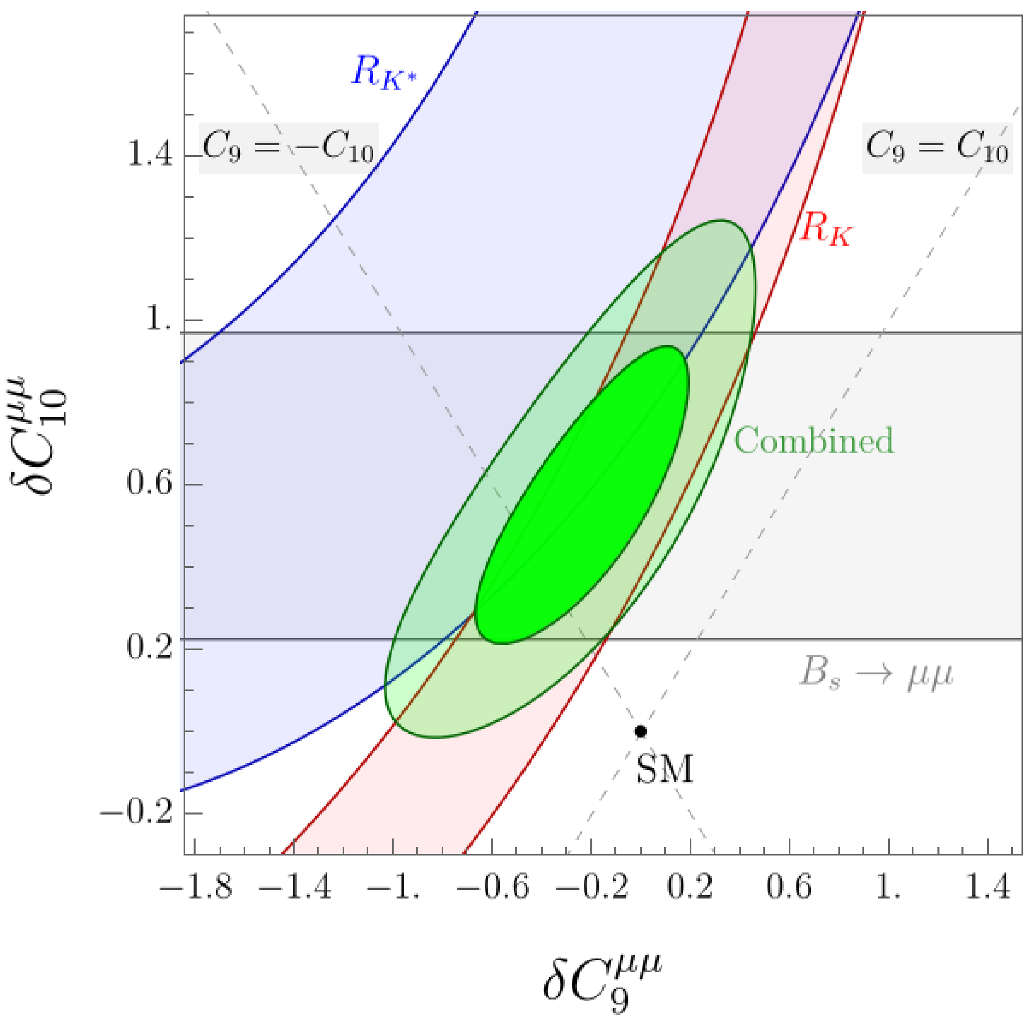
[Our average, CMS, ATLAS, LHCb]

[Beneke et al. '19]

Combined fit

[Angelescu, Becirevic, Faroughy, Jaffredo, **OS**. '21]

Clean quantities



- Only vector(axial) coefficients can accommodate data.
- $C'_{9,10}$ disfavored by $R_{K^*}^{\text{exp}} < R_{K^*}^{\text{SM}}$
- Purely **left-handed** operator preferred $[4.6\sigma]$:

$$\delta C_9^{\mu\mu} = -\delta C_{10}^{\mu\mu}$$
$$= -0.41 \pm 0.09$$

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

From EFT to concrete models

Concrete models for R_K & R_{K^*}

- Few $SU(2)_L \times U(1)_Y$ invariant operators predict $C_9^{\mu\mu} = -C_{10}^{\mu\mu}$:

$$O_{lq}^{(1)} = (\overline{L}\gamma^\mu L)(\overline{Q}\gamma_\mu Q)$$

$$O_{lq}^{(3)} = (\overline{L}\gamma^\mu \tau^I L)(\overline{Q}\gamma_\mu \tau^I Q)$$

NB. LFU breaking operators!

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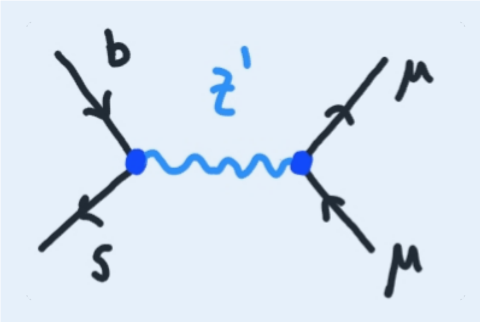
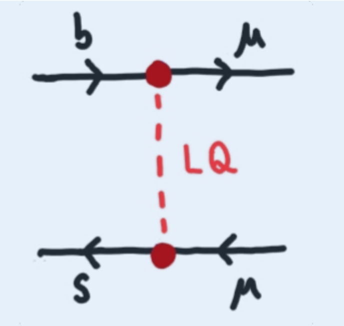
NB. LFU breaking operators!

- **Tree-level** mediators:

$$\frac{g_{\rm NP}}{\Lambda} \approx \frac{1}{30\ \mathrm{TeV}}$$





$(SU(3)_c, SU(2)_L, U(1)_Y)$ $\qquad$ $(\mathbf{1},\mathbf{1},0)$ or $(\mathbf{1},\mathbf{3},0)$ $\qquad$ $(\mathbf{3},X,Y)$

- **Loop-level** scenarios are **tightly constrained**: LHC, $Z \to \mu\mu$, Δm_{B_s} ...

see e.g. [Coy, Frigerio, Mescia, **OS**. '19]

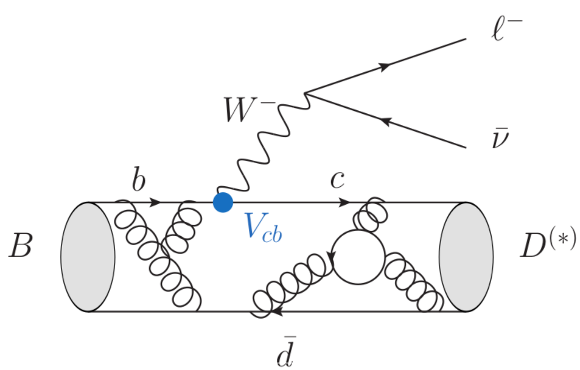
Charged-current B-anomalies

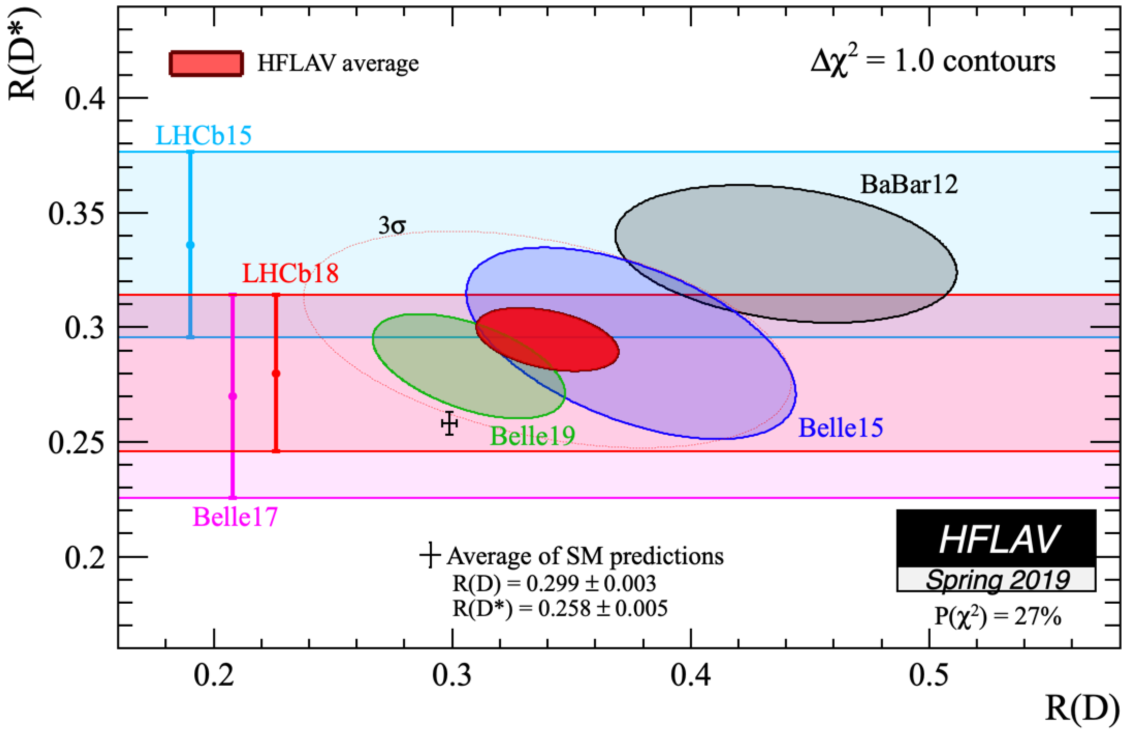
R_D & R_{D^*}

A piece of the same puzzle?

$[\approx 3.1\sigma]$

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\mu\bar{\nu})}$$





- R_D and R_{D^*} : **dominated by BaBar**.
- LHCb confirmed tendency $R^{\text{exp}}_{J/\psi} > R^{\text{SM}}_{J/\psi}$, i.e. $B_c \to J/\psi \ell \bar{\nu}$

Needs clarification from **Belle-II** and **LHCb (run-2)** data!

SM predictions

Form-factors:

- R_D : lattice QCD at $q^2 \neq q^2_{\rm max}$ ($w \neq 1$) available for both leading (vector) and subleading (scalar) form factors:

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

with $f_+(0) = f_0(0)$. [MILC/Fermilab '15, HPQCD, '15]

- R_{D^*} : lattice QCD at $q^2 \neq q^2_{\rm max}$ ($w \neq 1$) not yet available, scalar form factor [$A_0(q^2)$] never computed on the lattice.

Use $B \to D^*(D\pi)l\bar{\nu}$ $(l = e, \mu)$ angular distributions measured at B-factories to fit the leading form factor $[A_1(q^2)]$ and extract two others as ratios w.r.t. $A_1(q^2)$. All other ratios from HQET (NLO in $1/m_{c,b}$) [Bernlochner et al. '17] but with more generous error bars (truncation errors?)

[Preliminary LQCD results by MILC/Fermilab, 1912.05886]

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

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

General messages:

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

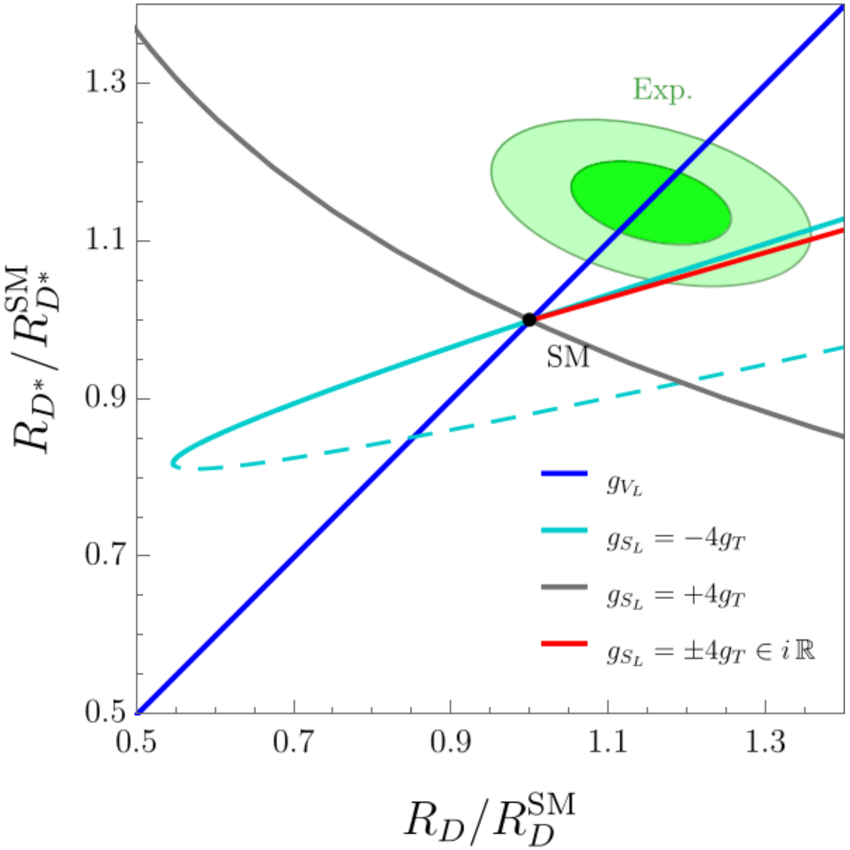
- Several viable solutions to $R_{D^{(*)}}$:
  - $\Rightarrow$ e.g. $g_{V_L} \in (0.05,\, 0.09)$, **but not only**!

[Angelescu, Becirevic Faroughy, Jaffredo, **OS**, '21]

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

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

Which operators to pick?



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

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

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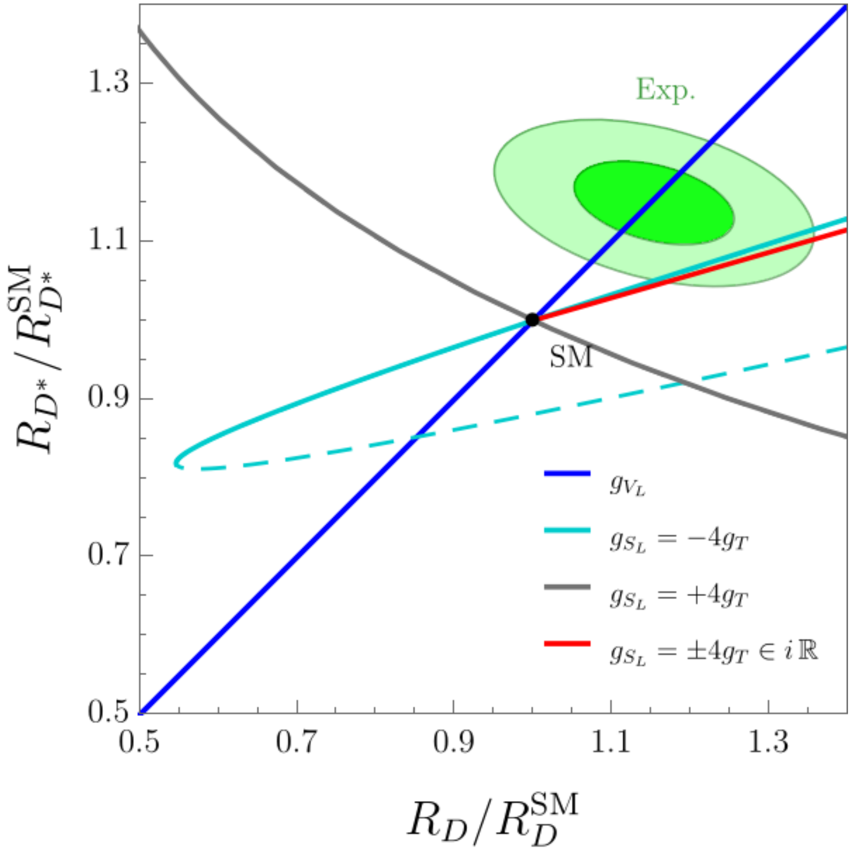


Viable solutions (at $\mu \approx 1$ TeV):

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

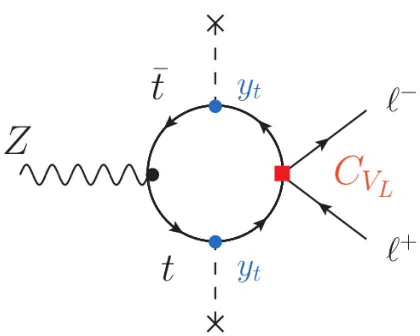
More **exp. information** is **needed**:

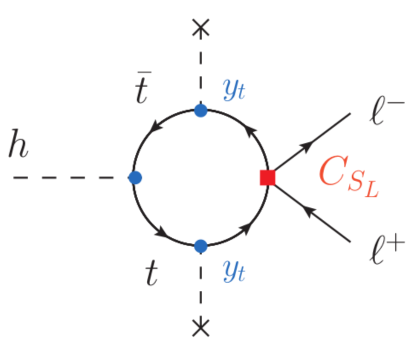
$\Rightarrow$ e.g., angular observables:

$B \to D\tau\bar{\nu}$ $\quad$ $B \to D^*(D\pi)\tau\bar{\nu}$

[Becirevic, Jaffredo, Peñuelas, **OS**. '20]

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





Electroweak observables can also be a useful handle!

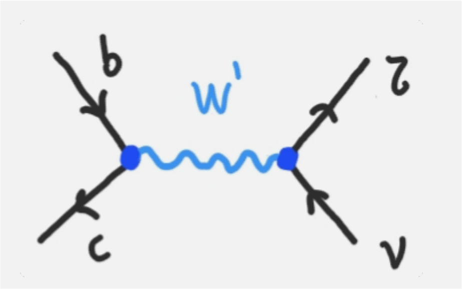
[Feruglio et al. '17]

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

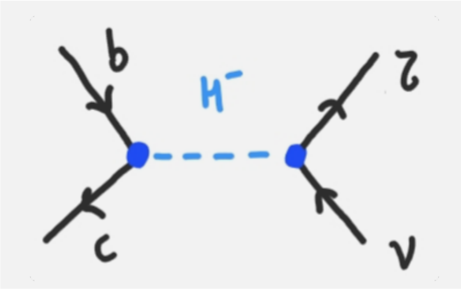
Explaining $b \to c\tau\bar{\nu}$

- $R_{D^*}^{\rm exp} > R_{D^*}^{\rm SM}$ require new bosons at $\Lambda_{\rm NP} \lesssim 3$ TeV .

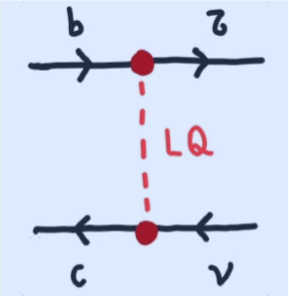
- Possible **tree-level mediators**:



$(\mathbf{1}, \mathbf{3}, 0)$



$(\mathbf{1}, \mathbf{2}, 1/2)$



$(\mathbf{3}, X, Y)$

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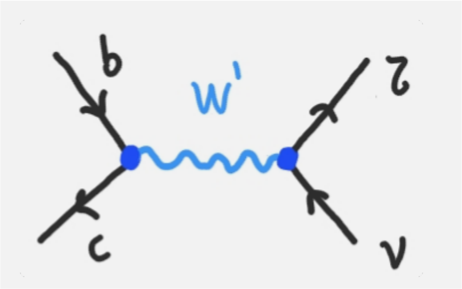

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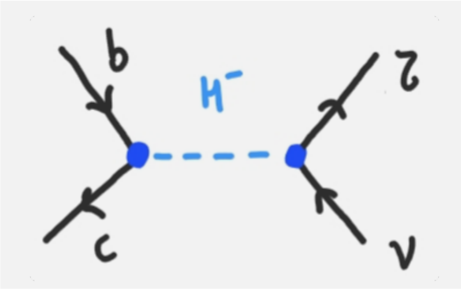

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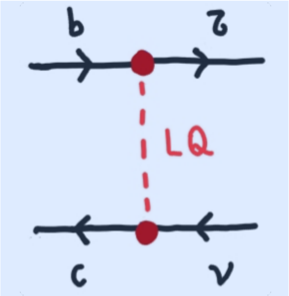

$(\mathbf{3},X,Y)$

- **Challenges** for **New Physics** explanations:

$\Rightarrow$ Flavor observables: $B \to K\nu\bar{\nu},\ \Delta m_{B_s},\ldots$ [Many papers...]

$\Rightarrow$ Electroweak constraints (one-loop): $\tau \to \mu\nu\bar{\nu},\ Z \to \ell\ell$ [Feruglio et al. '16]

$\Rightarrow$ LHC direct and indirect bounds. [Eboli. '88, Greljo et al. '15, Faroughy et al. '16]

Explaining $b \to c\tau\bar{\nu}$

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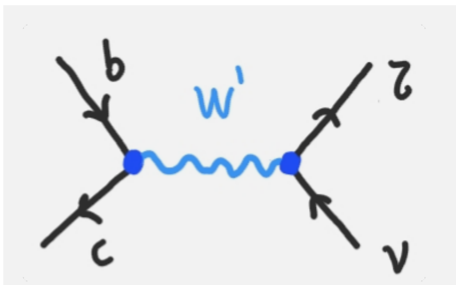
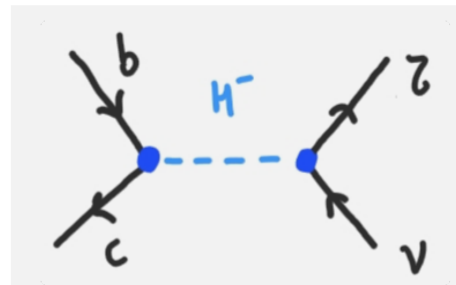


$(\mathbf{1}, \mathbf{3}, 0)$



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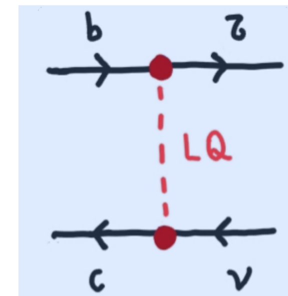

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Scalar and vector **leptoquarks** are the **only viable candidates**

Which leptoquark?

[Angelescu, Becirevic Faroughy, Jaffredo, **OS**, '21]

Few viable scenarios!

$$(SU(3)_c, SU(2)_L, U(1)_Y)$$

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

Which leptoquark?

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S_3 $(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	✓	✗	✗
S_1 $(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✗	✓	✗
R_2 $(\mathbf{3}, \mathbf{2}, 7/6)$	✗	✓	✗
U_1 $(\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓
U_3 $(\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗	✗

- Only the U_1 LQ can do the job alone, but <u>UV completion needed</u>.

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

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

  [Di Luzio et al. '17, Bordone et al. '18...]

- Two scalar LQs are also viable:

  $\Rightarrow$ S_1 and S_3, or R_2 and S_3.

[Crivellin et al. '17, Mazzocca. '18] [Becirevic et al., '18]

Closing the leptoquark window

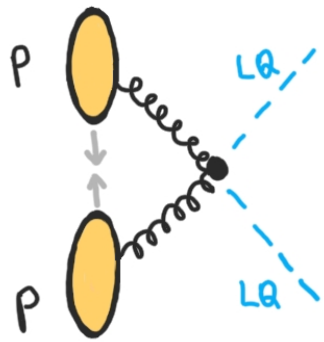
[Angelescu, Becirevic Faroughy, Jaffredo, **OS**, '21]

LHC constraints

i) LQ pair production

Production dominated by QCD:

$$\sigma(pp \to \mathrm{LQ}\,\mathrm{LQ}^\dagger) \times \underbrace{\mathcal{B}(\mathrm{LQ} \to \ell q)^2}_{\equiv \beta^2}$$



$+ \ \ldots$

see [Dorsner et al.. '18] for a recent review

ATLAS and CMS results for $\beta = 1\,(\text{or } 0.5)$

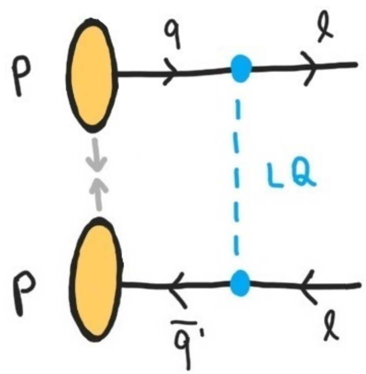
Decays	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\rm int}$ / Ref.
$jj\,\tau\bar{\tau}$	–	–	–
$b\bar{b}\,\tau\bar{\tau}$	1.0 (0.8) TeV	1.5 (1.3) TeV	36 fb^{-1} [39]
$t\bar{t}\,\tau\bar{\tau}$	1.4 (1.2) TeV	2.0 (1.8) TeV	140 fb^{-1} [40]
$jj\,\mu\bar{\mu}$	1.7 (1.4) TeV	2.3 (2.1) TeV	140 fb^{-1} [41]
$b\bar{b}\,\mu\bar{\mu}$	1.7 (1.5) TeV	2.3 (2.1) TeV	140 fb^{-1} [41]
$t\bar{t}\,\mu\bar{\mu}$	1.5 (1.3) TeV	2.0 (1.8) TeV	140 fb^{-1} [42]
$jj\,\nu\bar{\nu}$	1.0 (0.6) TeV	1.8 (1.5) TeV	36 fb^{-1} [43]
$b\bar{b}\,\nu\bar{\nu}$	1.1 (0.8) TeV	1.8 (1.5) TeV	36 fb^{-1} [43]
$t\bar{t}\,\nu\bar{\nu}$	1.2 (0.9) TeV	1.8 (1.6) TeV	140 fb^{-1} [44]

[Angelescu, Becirevic Faroughy, Jaffredo, **OS**, '21]

LHC constraints

ii) di-lepton production at high-p_T

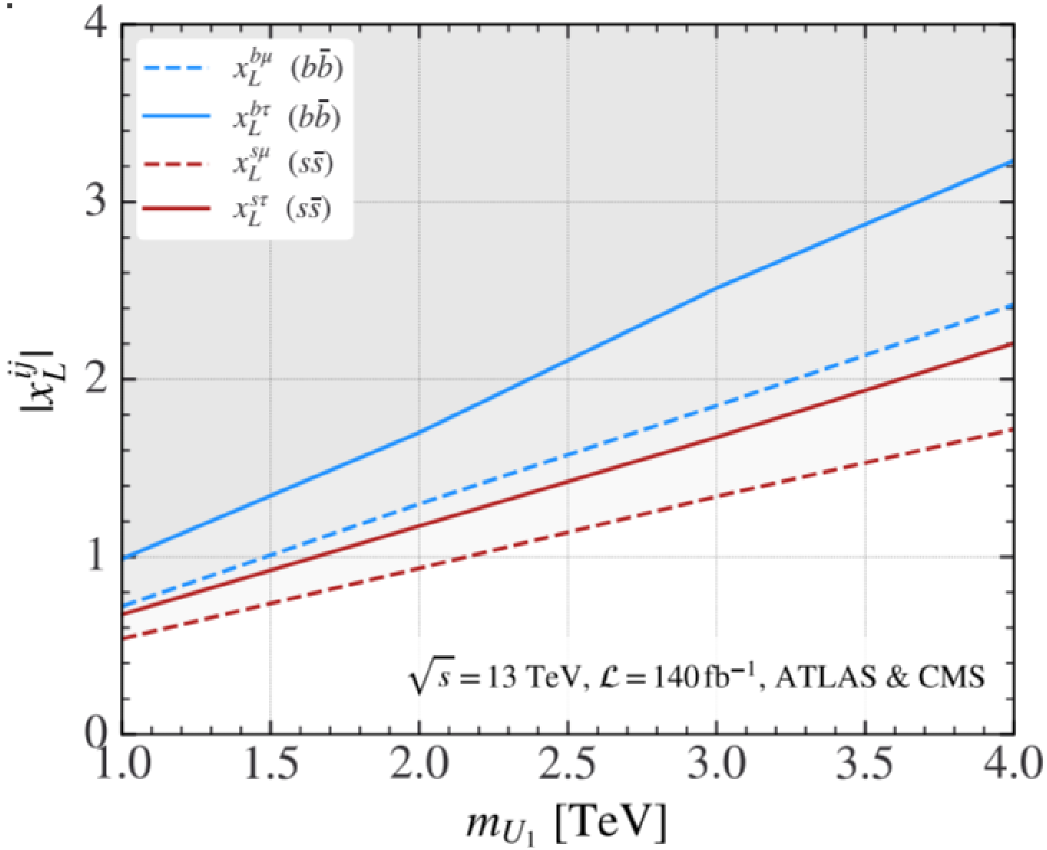
Useful upper limits on **LQ couplings**:



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

$$\mathcal{L}_{U_1} = x_L^{ij}\, \overline{Q}_i \gamma^\mu L_j\, U_1^\mu + \text{h.c.}$$

[ATLAS and CMS]



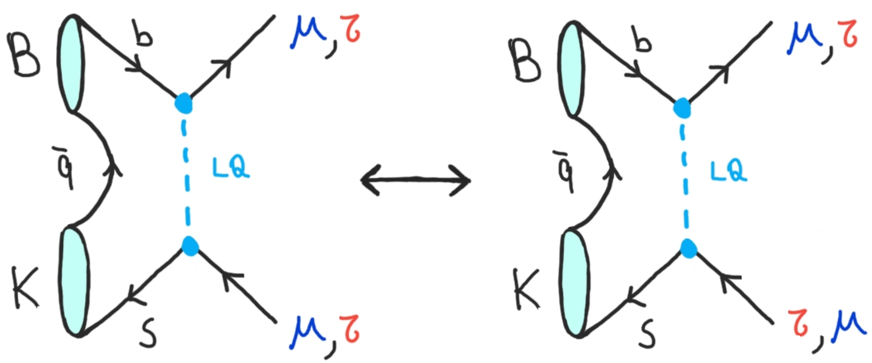
[Angelescu, Becirevic Faroughy, Jaffredo, **OS**, '21]

First considered for leptoquarks by [Eboli, '88].

Combining flavor and LHC

[Angelescu, Becirevic, Faroughy Jaffredo, **OS**. '21]

- **LFU**V $\leftrightarrow$ **L**epton **F**lavor **V**iolation



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

Predictions for

[Glashow et al. '14]

$$B_s \to \mu\tau \qquad B \to K^{(*)}\mu\tau$$

New searches $(95\%\,\mathrm{CL})$**:**

$$\mathcal{B}(B_s \to \mu^\pm\tau^\mp)^{\mathrm{exp}} < 4.2 \times 10^{-5}$$
$$\mathcal{B}(B^+ \to K^+\mu^-\tau^+)^{\mathrm{exp}} < 4.5 \times 10^{-5}$$

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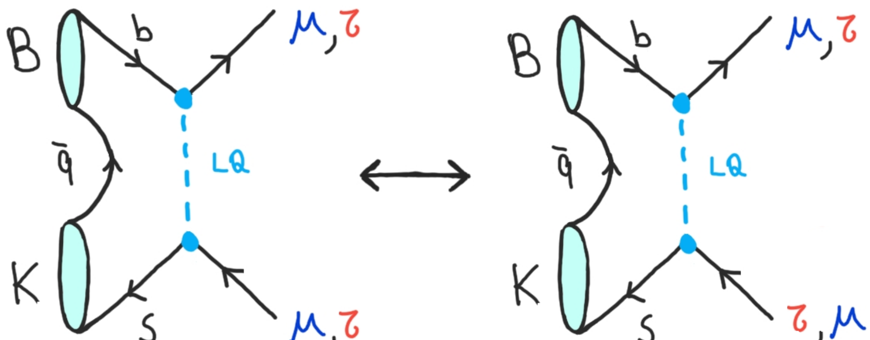

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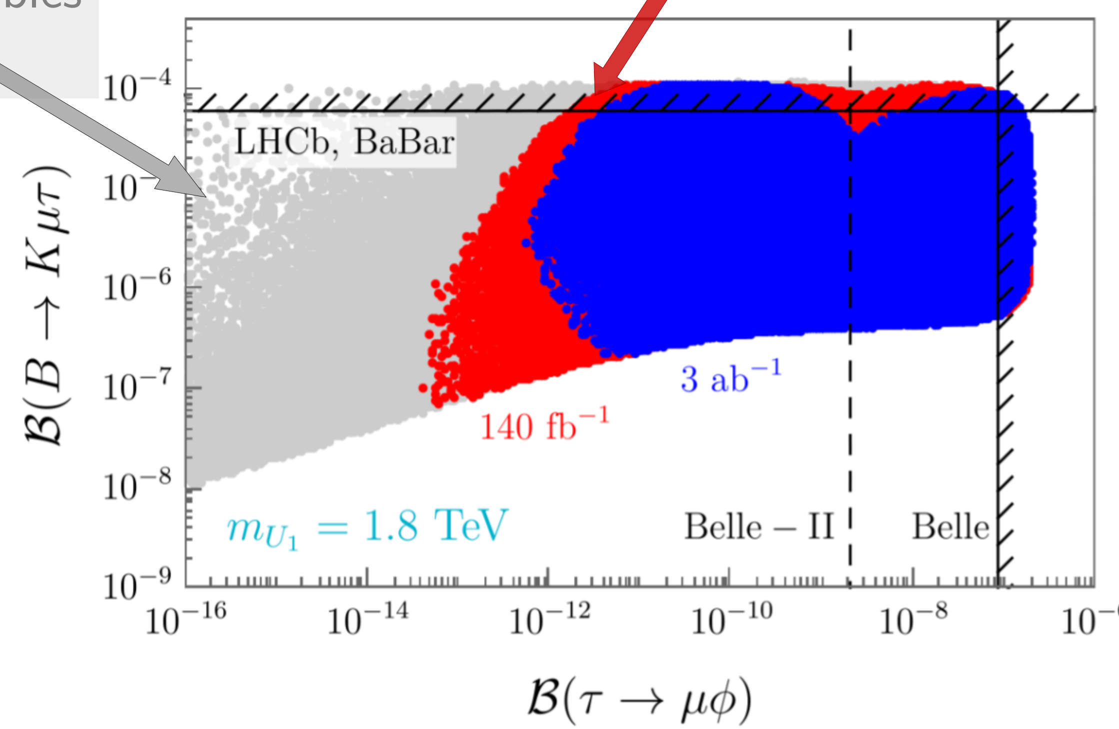
LHC constraints

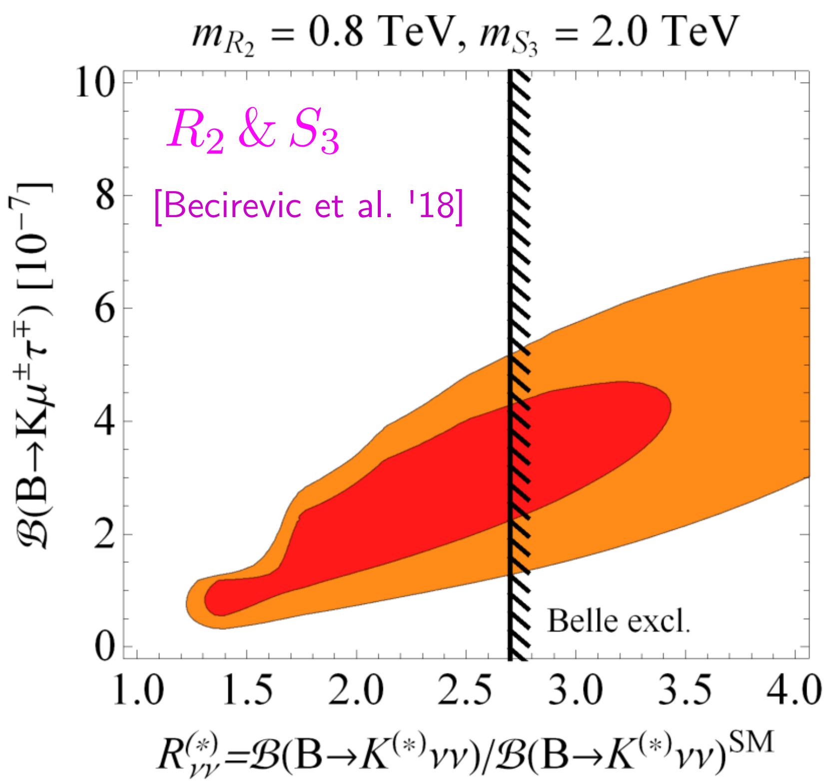
Several flavor observables (at tree-level)

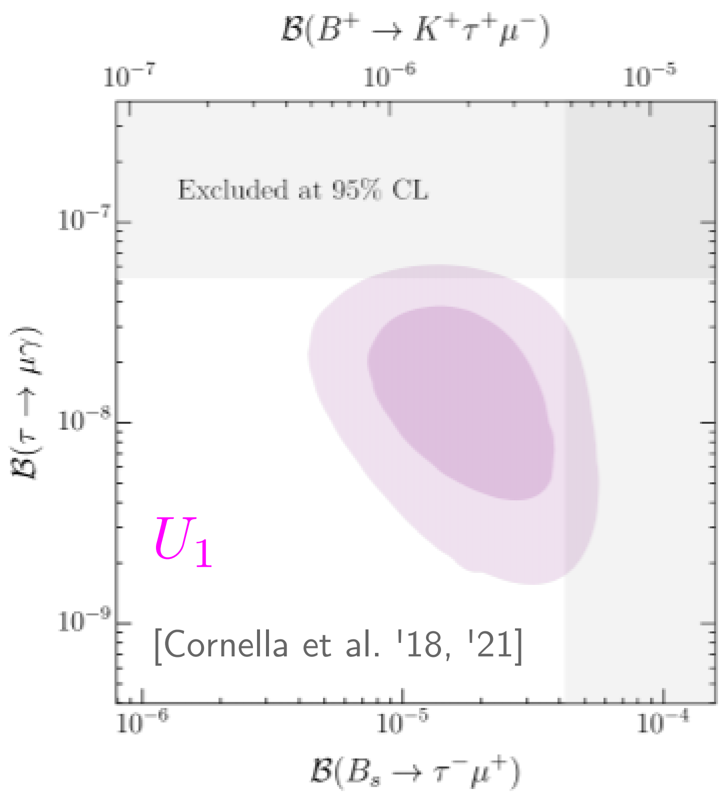


High-p$_T$ constraints set a model-independent **lower bound** on $\mathcal{B}(B \to K\mu\tau)$

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]





EFT predictions:

[Becirevic, **OS**, Zukanovich. '18]

i. LH operators:

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

ii. Scalar operators:

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

B-decays with missing energy

e.g. [Becirevic et al. '18]

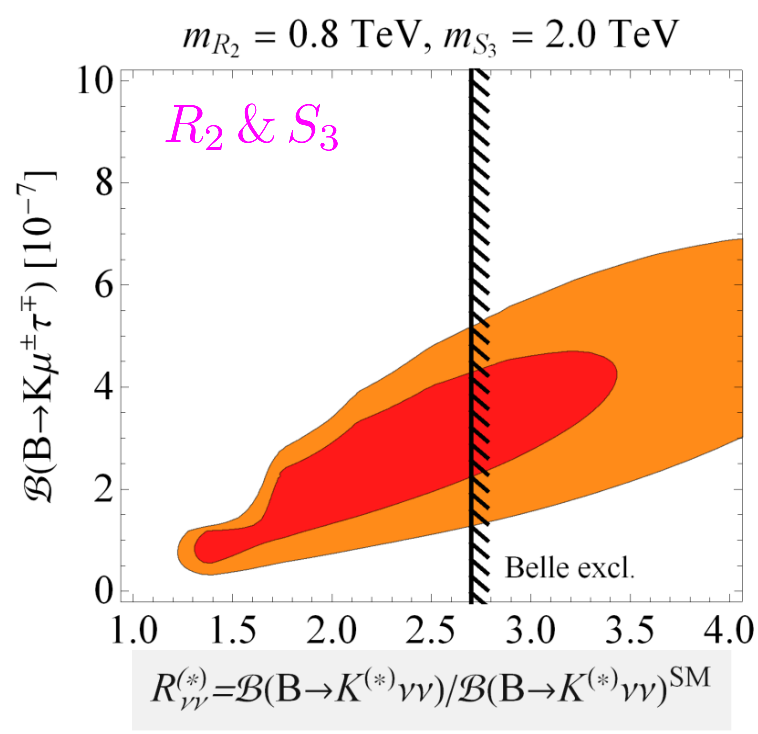
- **Clean observable** in the SM:

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})^{\rm SM} = 4.6(5) \times 10^{-6}$$

[Blake et al. 1606.00916]

- Models for the ***B*-anomalies predict sizable deviations** from SM.

- **Unique access** to operators with τ-leptons; i.e. $L_3 = (\nu_{\tau L}, \tau_L)^T$.



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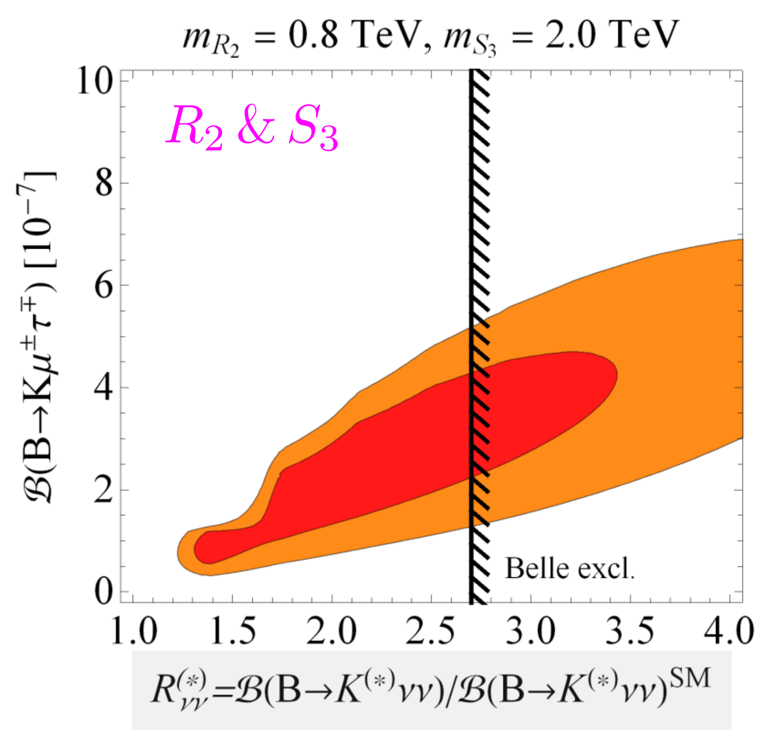
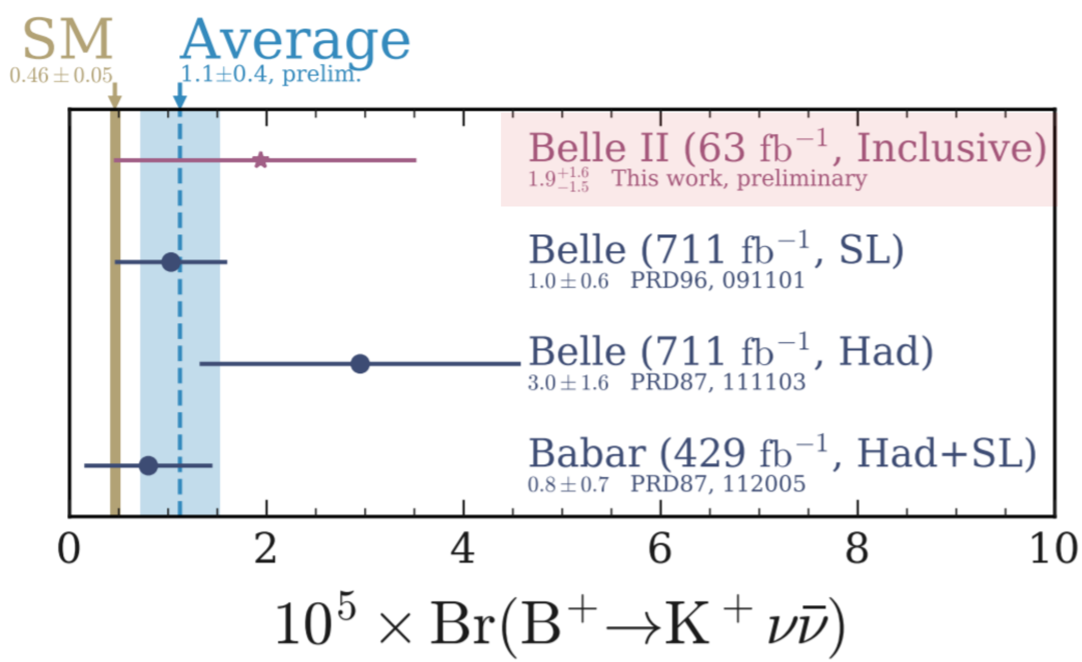




Promising results from early **Belle-II data**!

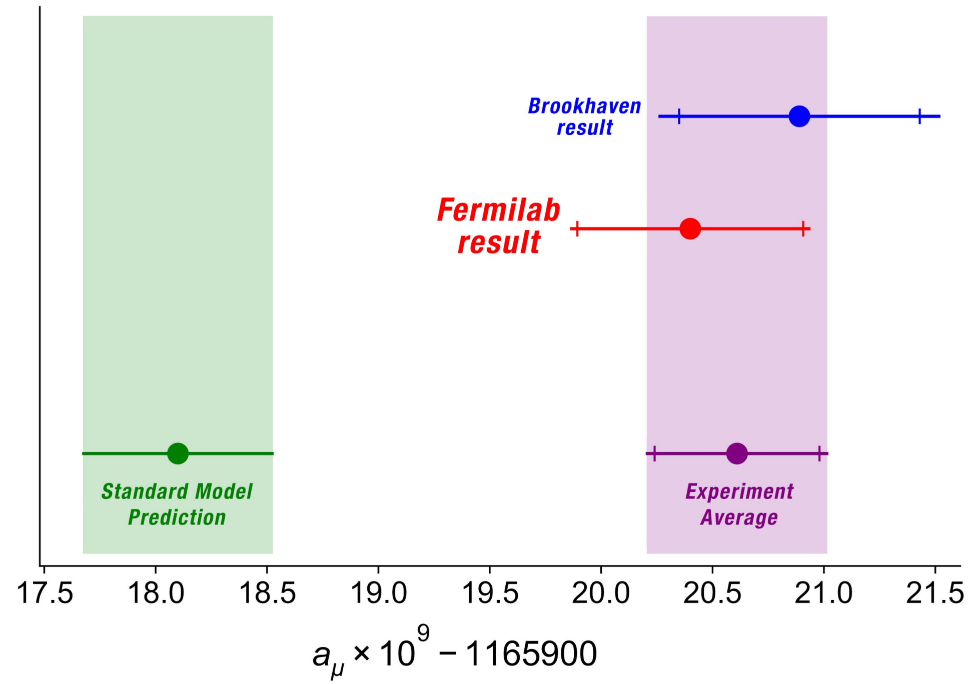
Muon g-2: another LFU hint?

Muon g-2

- **Exciting results** from Fermilab g-2 Muon experiment!

$[4.1\sigma]$ **deviation** from the **SM** prediction obtained in the **TH white paper**

[g-2 TH Initiative, '20]



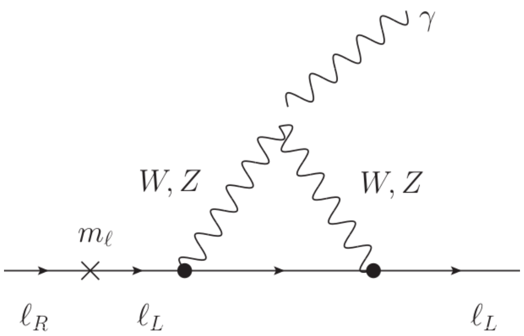
To be clarified: disagreement between **lattice QCD (BMW collaboration)** and **dispersive determinations** of **HVP**. Possible interplay with SM EW fit.

[BMWc, '20] [Keshavarzi et al. '20, Crivellin et al. '20]

Question: Can this discrepancy be **related** to the ***B*-anomalies**?

EFT for $(g-2)_\mu$

- **Chirality-conserving** contributions only possible for **light New Physics**:



$$\mathcal{L} \supset \frac{y_\mu}{16\pi^2} \frac{C_{\mathrm{D}}^{ij}}{\Lambda^2} \overline{L_i} H \sigma^{\alpha\beta} e_{R_j} F_{\alpha\beta} + \text{h.c.}$$

$$\Rightarrow \quad \boxed{\frac{C_D^{22}}{\Lambda^2} \approx \frac{1}{(100\ \text{GeV})^2}}$$

see e.g. [Biggio, Di Luzio. '16]

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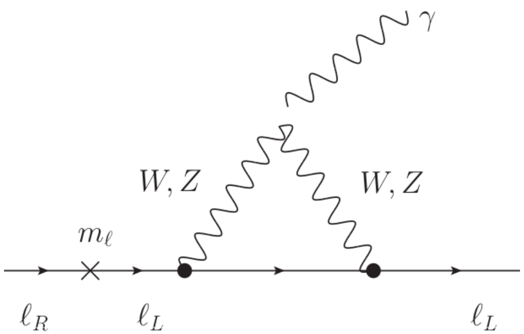

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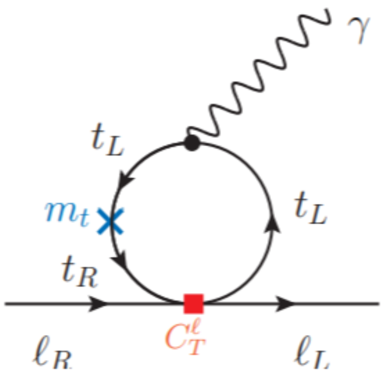
see e.g. [Biggio, Di Luzio. '16]

$$\Rightarrow \quad \boxed{\frac{C_D^{22}}{\Lambda^2} \approx \frac{1}{(100\ \text{GeV})^2}}$$

- **Chirality-enhancement** needed to accommodate $\Lambda \gtrsim 1\ \text{TeV}$:



$$C_D^{ij} \propto C_{sl}\frac{m_t}{m_\mu}\log\frac{\Lambda}{m_q} \quad \Rightarrow \quad \boxed{\frac{C_{sl}}{\Lambda^2} \approx \frac{1}{(100\ \text{TeV})^2}}$$

e.g.,

$$O_{lequ}^{(3)} = (\overline{L}^i\sigma_{\mu\nu}e_R)\epsilon_{ij}(\overline{Q}^j\sigma^{\mu\nu}u_R)$$

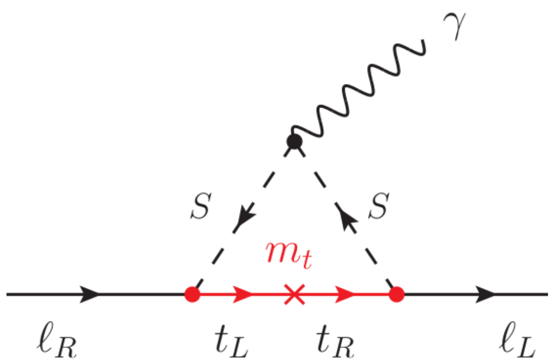
[Feruglio, Paradisi, **OS**, '18]

[Buttazzo et al. '20], [Fajfer et al. '21],[Aebischer et al., '21]

These contributions can be generated by **leptoquarks**! But **which one**?

Scalar LQs for $(g-2)_\mu$

- LQs should couple to $\bar{\mu}_L q_R\, S$ and $\bar{\mu}_R q_L\, S$:



Symbol	$(SU(3)_c, SU(2)_L, U(1)_Y)$	Interactions	$F = 3B + L$
S_3	$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	$\overline{Q}^C L$	-2
R_2	$(\mathbf{3}, \mathbf{2}, 7/6)$	$\overline{u}_R L$, $\overline{Q} e_R$	0
$\widetilde{R}_2$	$(\mathbf{3}, \mathbf{2}, 1/6)$	$\overline{d}_R L$	0
$\widetilde{S}_1$	$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	$\overline{d}_R^C e_R$	-2
S_1	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$\overline{Q}^C L$, $\overline{u}_R^C e_R$	-2

[Cheung. '01], [Crivellin et al. '20], [Dorsner,Fajfer, **OS**. '19]

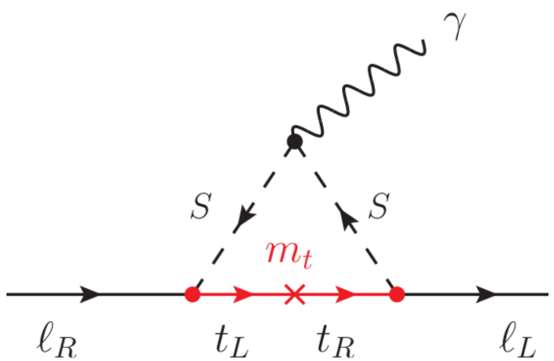
$\Rightarrow$ Two viable candidates (R_2 and S_1), but *not the ones needed for* $R_{K^{(*)}}$.

$\Rightarrow$ Connection to $R_{D^{(*)}}$ is difficult due to *LFV bounds*: $\tau \to \mu\gamma$.

See [Gherardi et al., '20] for the best attempt so far; tuning needed to avoid LFV bounds, tension with Δm_{B_s} (?) .

Scalar LQs for $(g-2)_\mu$

- LQs should couple to $\bar{\mu}_L q_R\, S$ and $\bar{\mu}_R q_L\, S$:



Symbol	$(SU(3)_c, SU(2)_L, U(1)_Y)$	Interactions	$F=3B+L$
S_3	$(\mathbf{\bar{3}}, \mathbf{3}, 1/3)$	$\overline{Q}^C L$	-2
R_2	$(\mathbf{3}, \mathbf{2}, 7/6)$	$\overline{u}_R L$, $\overline{Q} e_R$	0
$\widetilde{R}_2$	$(\mathbf{3}, \mathbf{2}, 1/6)$	$\bar{d}_R L$	0
$\widetilde{S}_1$	$(\mathbf{\bar{3}}, \mathbf{1}, 4/3)$	$\bar{d}_R^C e_R$	-2
S_1	$(\mathbf{\bar{3}}, \mathbf{1}, 1/3)$	$\overline{Q}^C L$, $\overline{u}_R^C e_R$	-2

[Cheung. '01], [Crivellin et al. '20], [Dorsner,Fajfer, **OS**. '19]

$\Rightarrow$ Two viable candidates (R_2 and S_1), but *not the ones needed for* $R_{K^{(*)}}$.

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Minimal solutions to ***B*-physics anomalies** and **muon g-2 do not point** to the **same interactions**. Possible in next-to-minimal scenarios (many papers...)

Summary and perspectives

- Renewed interest on the B-physics anomalies since latest LHCb results.

  Belle-II will be fundamental to confirm/refute these results!

- Correlation with other flavor observables are unavoidable for the viable scenarios and can be further explored to disentangle them.

  LFU ratios, LFV B-meson decays, $B \to K^{(*)} \nu \bar{\nu}$ ...

- We identify the viable single-mediator explanations to $R_{K^{(*)}}$ and/or $R_{D^{(*)}}$. There is not a direct connection to $(g-2)_\mu$ in these minimal scenarios.

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

- U_1 model: we demonstrate a pronounced complementarity of flavor physics constraints with those obtained from high-p_T searches at the LHC.

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

- Building a minimal model to simultaneously explain the various anomalies in flavor observables remains a very challenging task.

Data-driven model building!

Thank you!

Back-up

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 $B \to D^{(*)}\mu\bar{\nu}/B \to D^{(*)}e\bar{\nu}$.

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)!

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

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

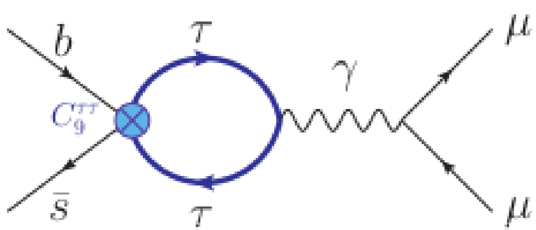
- Existing direct limits:

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

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

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

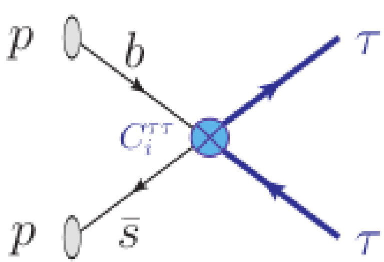
- New idea: deformation of $B \to K\mu\mu$ q^2-spectrum



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

[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!

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

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

and assume

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

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

$$\boxed{\text{Parameters: } m_{R_2},\ m_{S_3},\ y_R^{b\tau},\ y_L^{c\mu},\ y_L^{c\tau} \text{ and } \theta}$$