Theory overview of B-physics anomalies

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Lepton Flavor Universality (LFU)

- **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:

See also:

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

R_{pK}

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

$R_{J/\psi}$

[LHCb, *B-factories*]

- **If confirmed** with more data, they will be a clear evidence of **New Physics**!

Outline

I. Introduction

II. Lepton Flavor Universality

- Current status
- EFT interpretations
- From EFTs to complete models

III. From LFUV to high-p_T physics

IV. Predictions at low-energies

V. Summary

*See talk by F. Bernlochner on the experimental part!

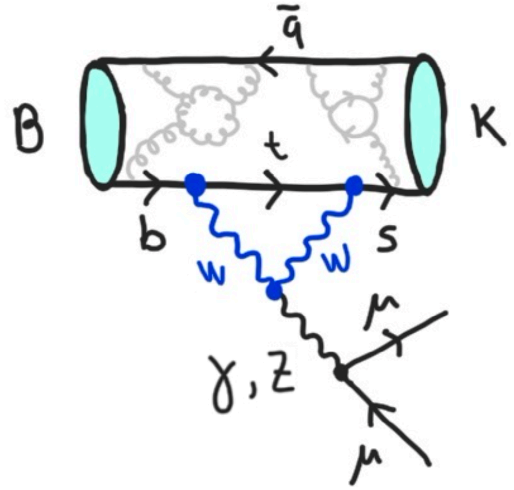
Introduction

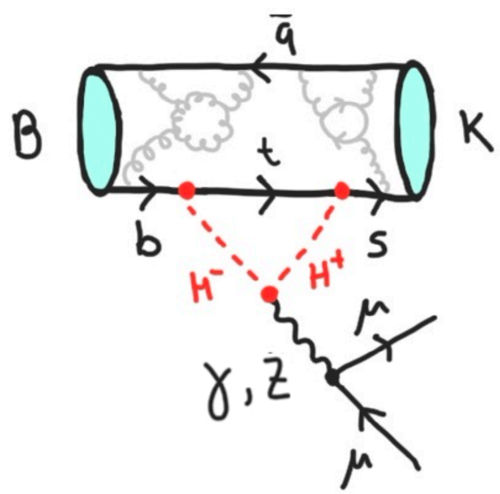
Seeking New Physics with flavor

Indirect searches of New Physics

i. Search deviations w.r.t. SM predictions:

e.g.,





$$\mathcal{O}_{\rm exp} = \mathcal{O}_{\rm SM}\,(1 + \delta_{\rm NP})$$

Both **exp.** and **theory** must be **precise**!

Look for observables:

- (Highly) sensitive to contributions from New Physics
- Mildly sensitive to hadronic uncertainties
- Accessible in current and/or (near) future experiments.

LFU ratios are an excellent example!

Indirect searches of New Physics

ii. Search processes forbidden (by accidental symmetries) in the SM

Global symmetry of the SM gauge sector:

$$U(3)^5 \equiv U(3)_Q \times U(3)_L \times U(3)_U \times U(3)_D \times U(3)_E$$

Broken by Yukawas to

$$U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

Examples:

- Proton decay **(BNV)**: $p \to \pi^0 e^+$
- $0\nu\beta\beta$ **(LNV):** $(A,Z) \to (A,Z+2) + 2e^-$
- **L**epton **F**lavor **V**iolation **(LFV):** $\mu \to e\gamma$

Clean probes of New Physics!

Lepton Flavor Universality

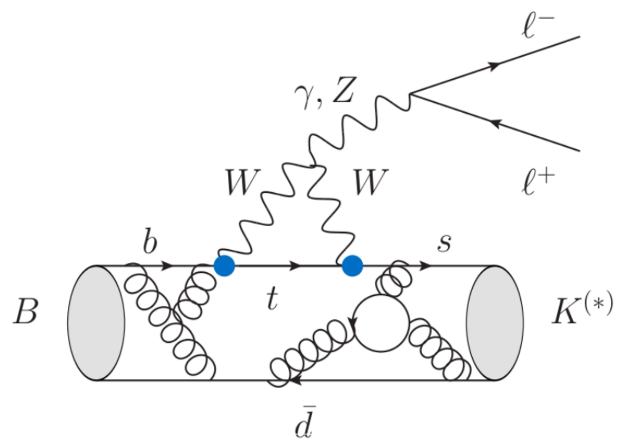
Current status

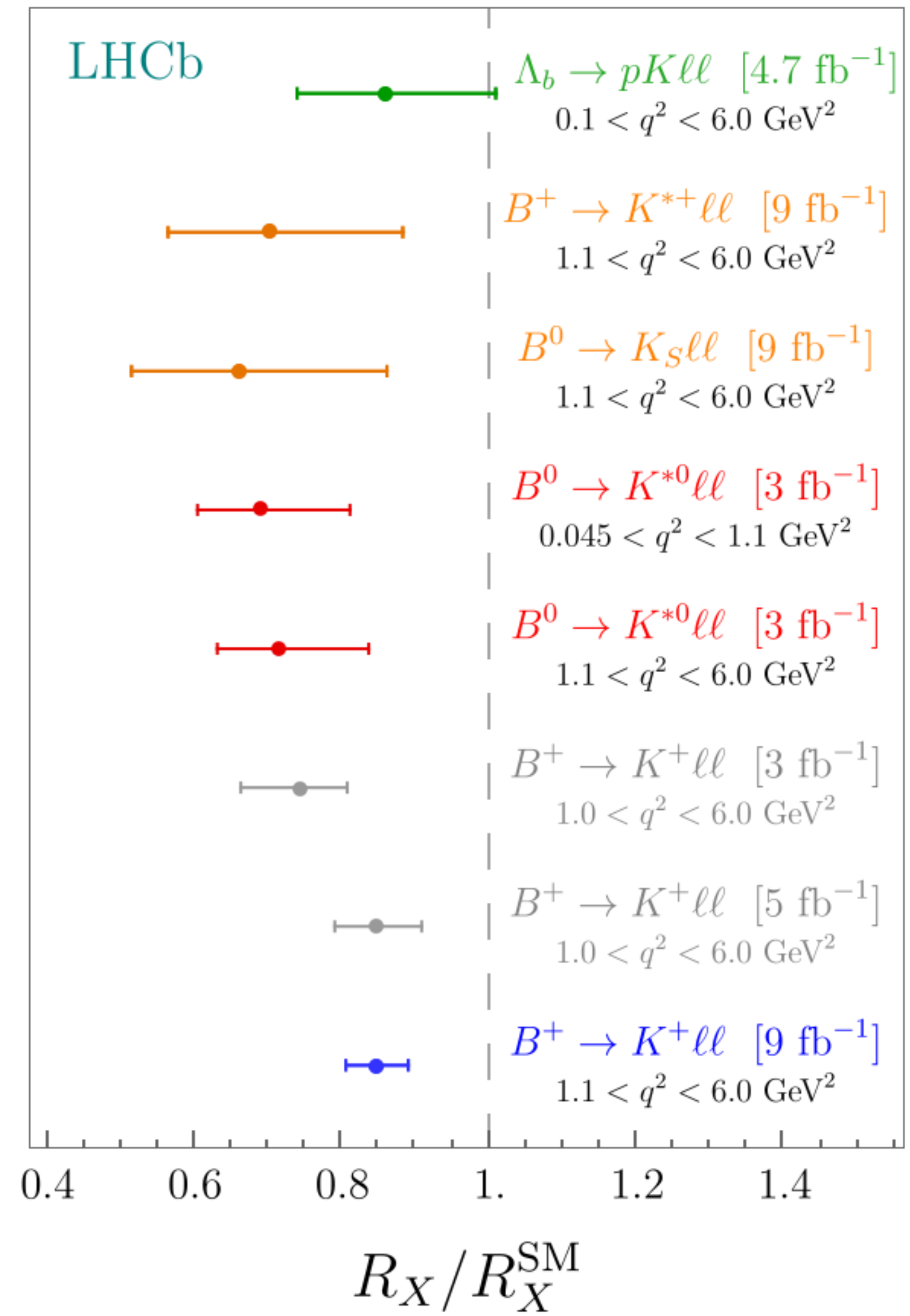
LFU in $b \to s\ell\ell$

Experiment

See talk by F. Bernlochner

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





Theory (loop induced)

- Hadronic uncertainties almost fully cancel.

  $\Rightarrow$ **Clean observables!** *[working below the narrow $c\bar{c}$ resonances]* [Hiller, Kruger. '04]

- However, QED corrections important, $R_{K^{(*)}}^{\rm SM} = 1.00(1)$ [Isidori et al. '20]

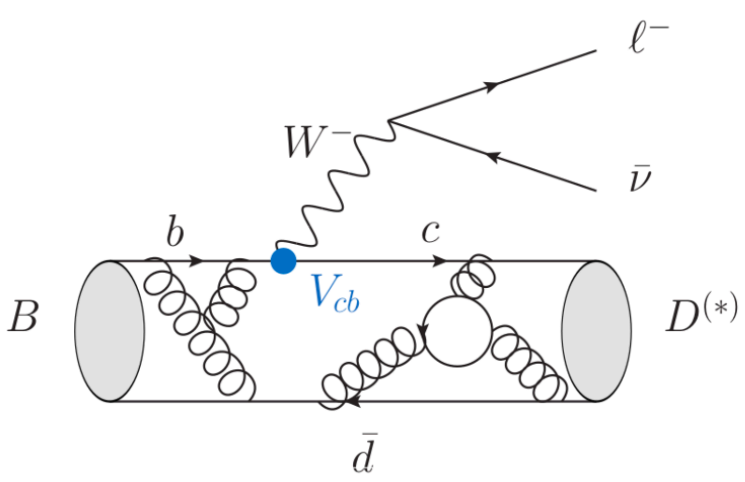
Needs independent cross-check from **Belle-II**

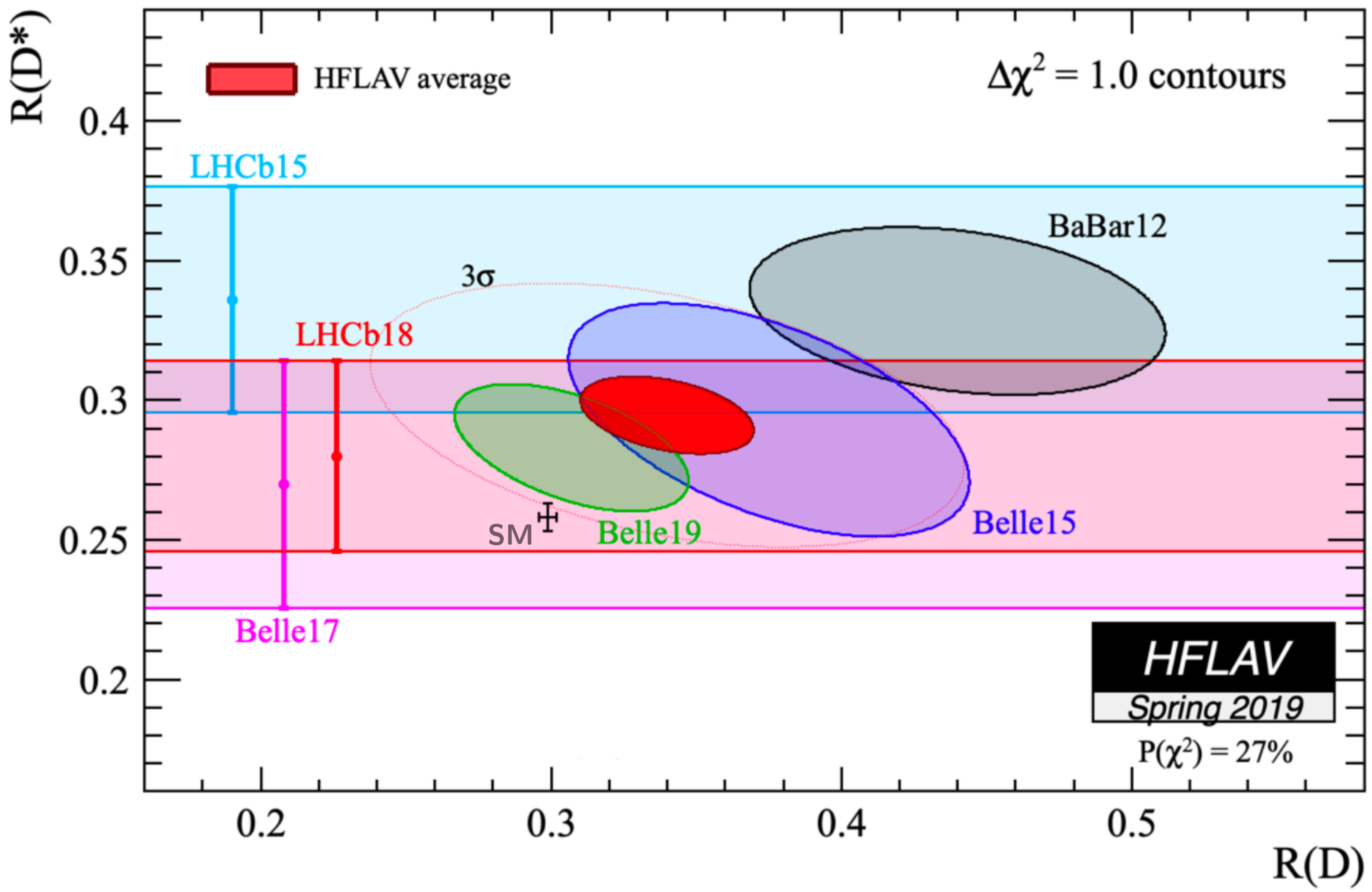
LFU in $b \to c\tau\bar{\nu}$

See talk by F. Bernlochner

Experiment

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

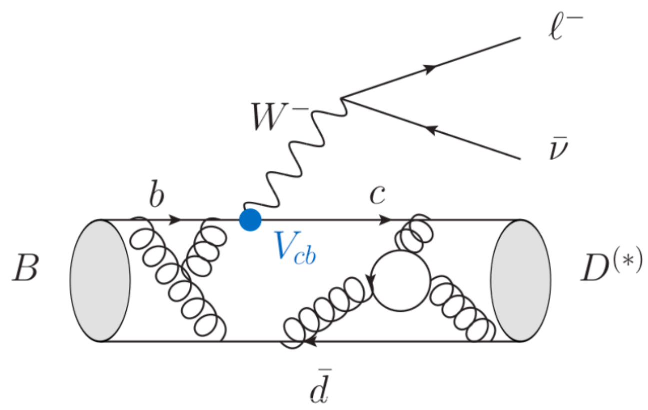




- R_D^{exp} and R_{D*}^{exp} : **dominated by BaBar!**
- LHCb confirmed tendency $R_{J/\psi}^{\text{exp}} > R_{J/\psi}^{\text{SM}}$, i.e. $B_c \to J/\psi \ell\bar{\nu}$ — *with large uncertainties.*

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

Form-factors: $B \to D^{(*)}\ell\bar{\nu}$

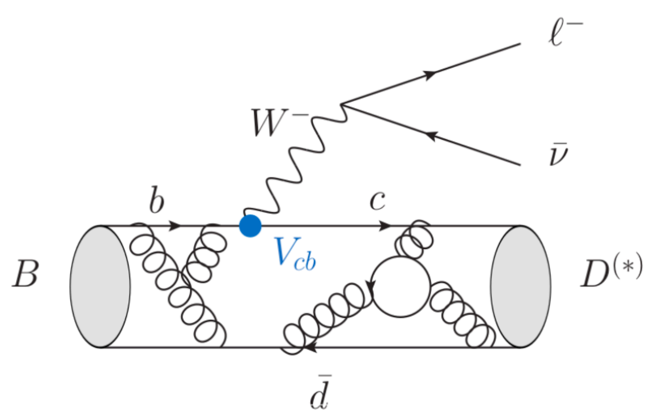


Known Lorentz factors

$$\langle D^{(*)}|\bar{c}_L\gamma^\mu b_L|B\rangle = \sum_a K_a^\mu\, \mathcal{F}_a(q^2)$$

Form-factors (from lattice, exp...)

Form-factors: $B \to D^{(*)} \ell \bar{\nu}$



Known Lorentz factors

$$\langle D^{(*)} | \bar{c}_L \gamma^\mu b_L | B \rangle = \sum_a K_a^\mu \, \mathcal{F}_a(q^2)$$

Form-factors (from lattice, exp...)

For light (heavy) leptons:

- $B \to D$: one (two) form-factors with $f_0(0) = f_+(0)$ at $q^2 = 0$;

  $\Rightarrow$ Lattice QCD at $q^2 \neq q^2_{\text{max}}$ $(w \neq 1)$ for both form-factors. [MILC/Fermilab '15, HPQCD '15]

$$R_D^{\text{latt.}} = 0.293(5) \qquad R_D^{\text{latt.+exp}} = 0.295(3)$$ [FLAG '21]

$B \to D^{(*)} l \bar{\nu} \quad (l = e, \mu)$

- $B \to D^*$: three (four) form-factors;

  $\Rightarrow$ [NEW] First lattice computation at $q^2 \neq q^2_{\text{max}}$ $(w \neq 1)$ [MILC/Fermilab '21]

$$R_{D^*}^{\text{latt.}} = 0.265(13) \qquad R_{D^*}^{\text{latt.+exp}} = 0.2483(13)$$ [See back-up!]

1.3σ apart ⚠

Way out: independent LQCD results + Belle-II!

New Physics interpretations

- EFT description
- From EFTs to concrete models

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

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

- **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 operator* is *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 exp. average: CMS, ATLAS, LHCb]

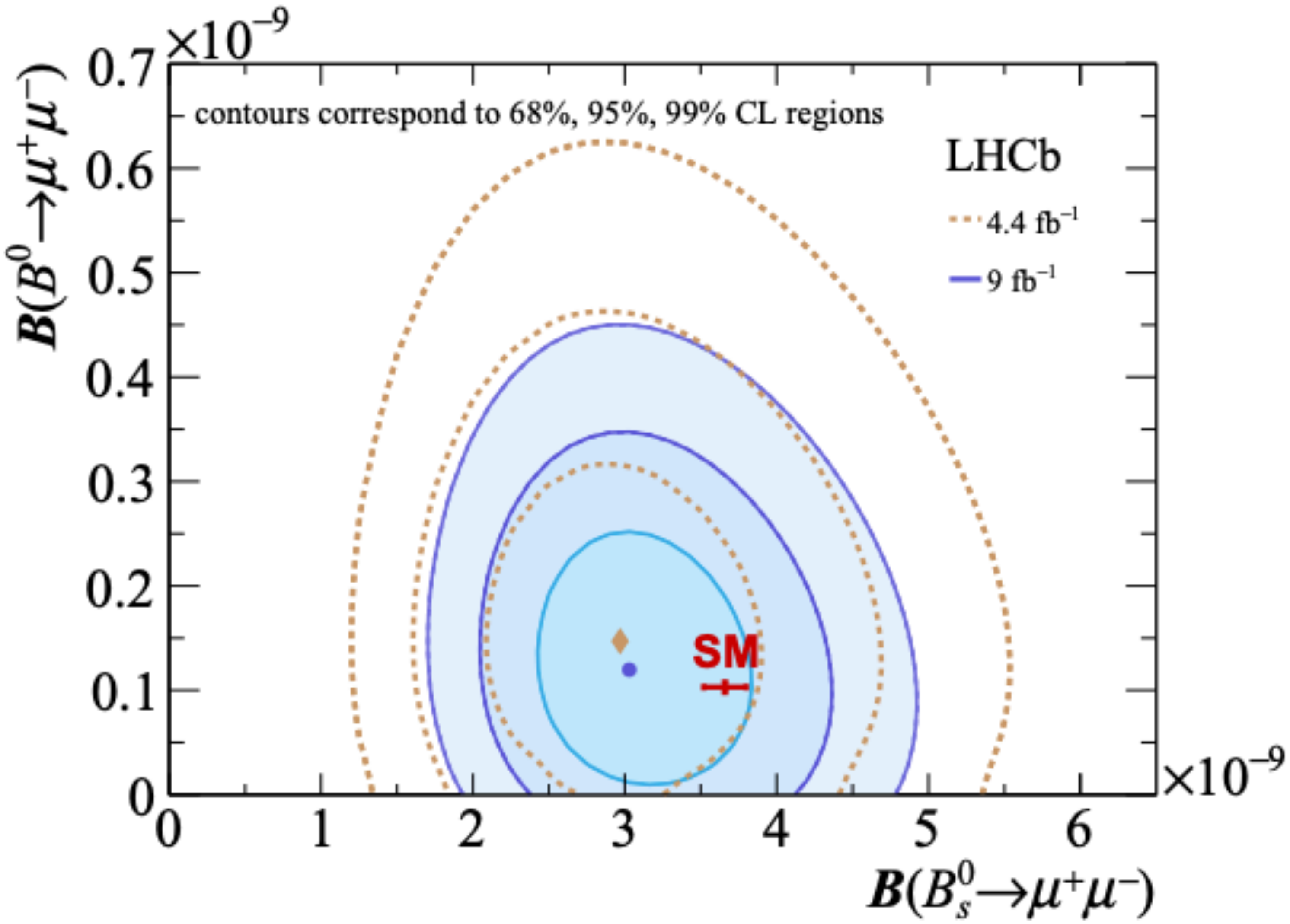
$$\overline{\mathcal{B}}(B_s \to \mu\mu)^{\text{SM}} = (3.66 \pm 0.14) \times 10^{-9}$$

[Beneke et al. '19]

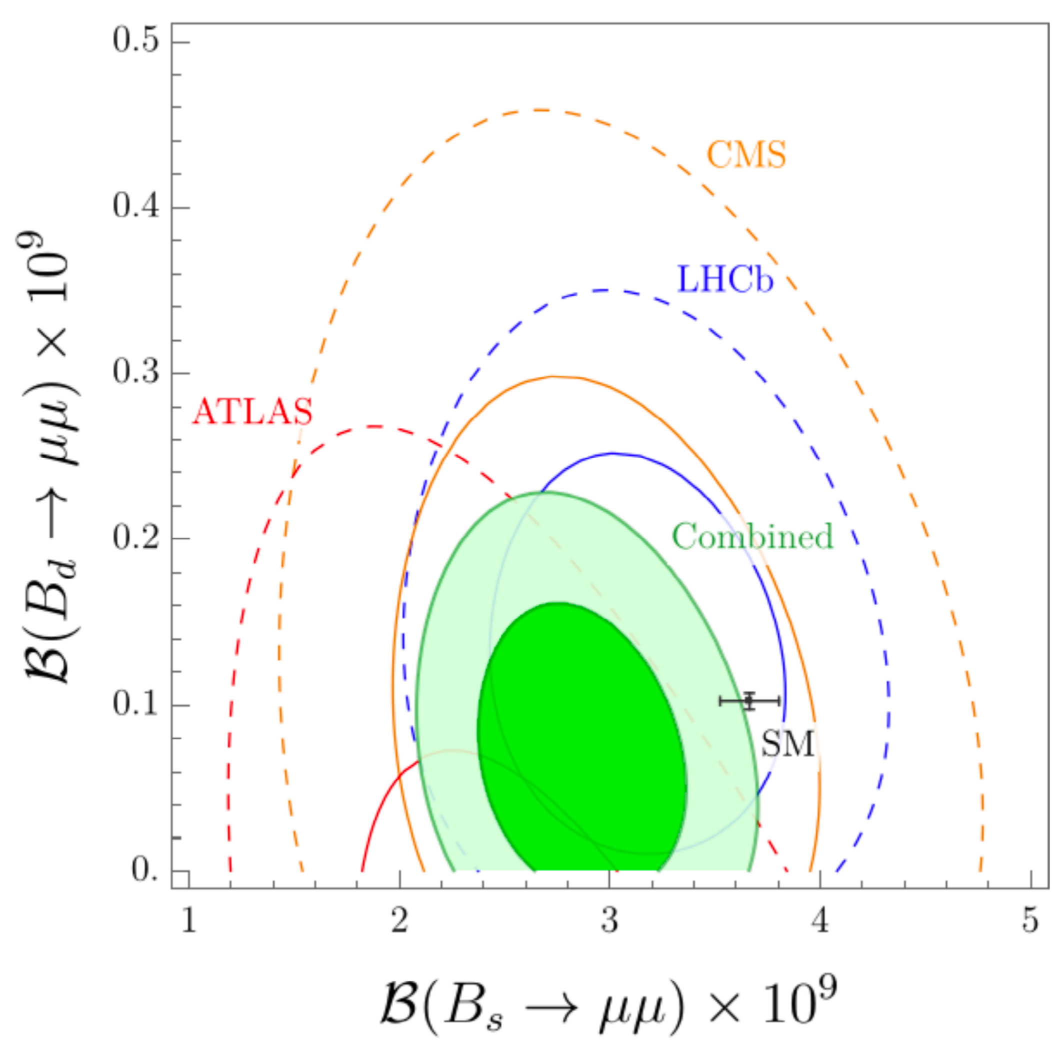
[Intermezzo] $B_s \to \mu\mu$

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

[LHCb '21]



[Our exp. average: CMS, ATLAS, LHCb]

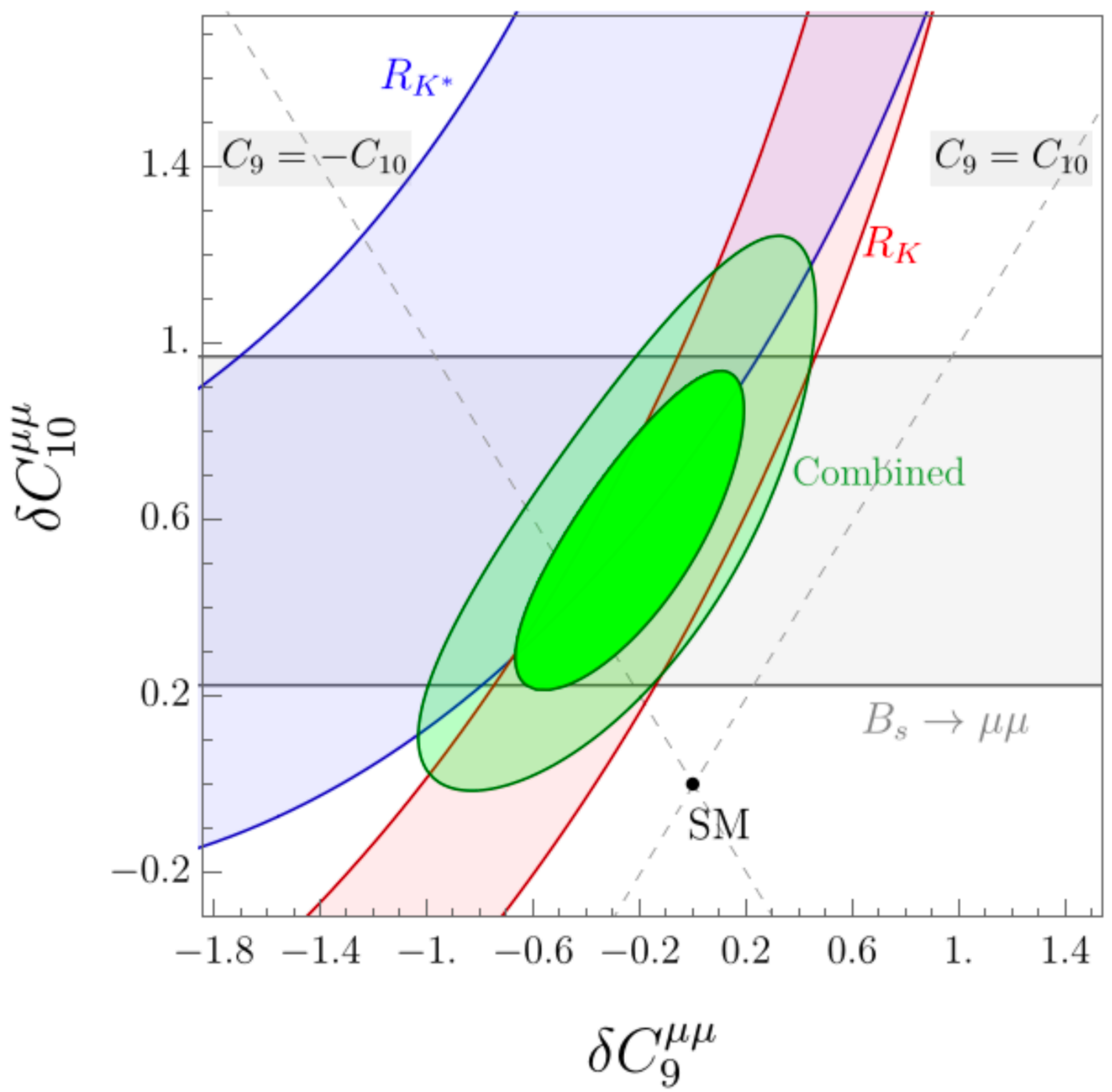


- **Good agreement** between **LHCb** results and the SM predictions;
- Small deficit in the exp. average — *due to ATLAS measurement.*

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

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

Clean quantities: R_K, R_{K^*} and $\mathcal{B}(B_s \to \mu\mu)$



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

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

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

[Algueró et al. '21, Altmannshofer et al. '21, Hurth et al. '21]

EFT for $b \to c\tau\bar{\nu}$

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

- $SU(3)_c \times SU(2)_L \times U(1)_Y$ 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 explanations of $R_{D^{(*)}}$:
  - $\Rightarrow$ e.g., $g_{V_L} = 0.07 \pm 0.02$, **but not only**!

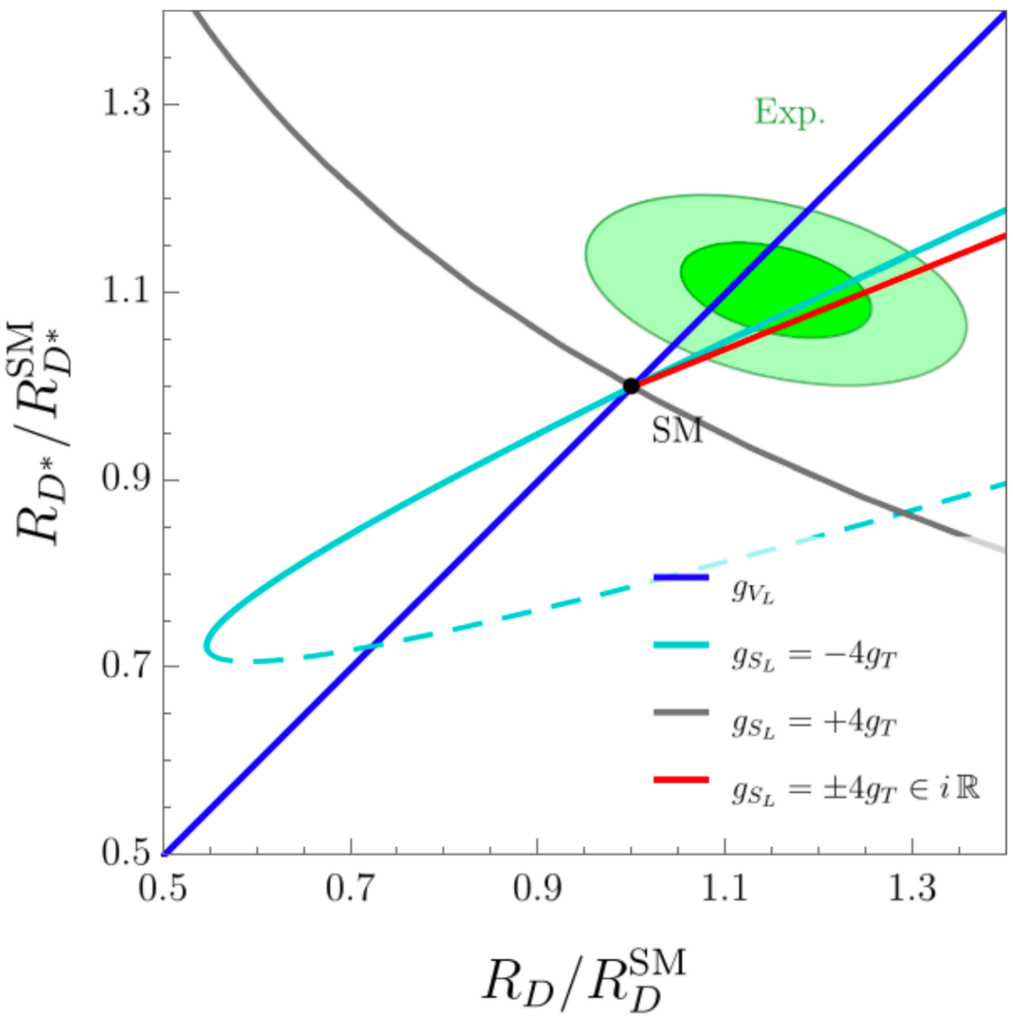
[Angelescu, Becirevic, Faroughy, Jaffredo, **OS**. '21]

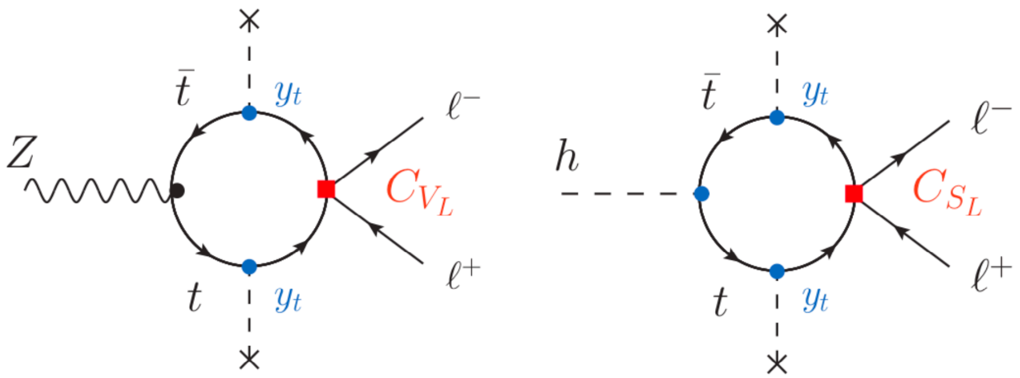
see also [Murgui et al. '19, Shi et al. '19, Blanke et al. '19]

EFT for $b \to c\tau\bar{\nu}$

Which operators to pick?

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





- 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/Higgs observables can also be an useful handle

[Feruglio et al. '17]

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

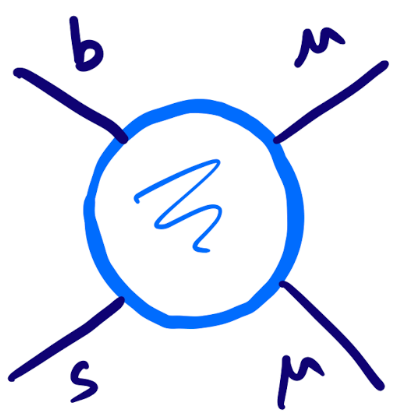
From EFTs to concrete models

From EFTs to concrete models

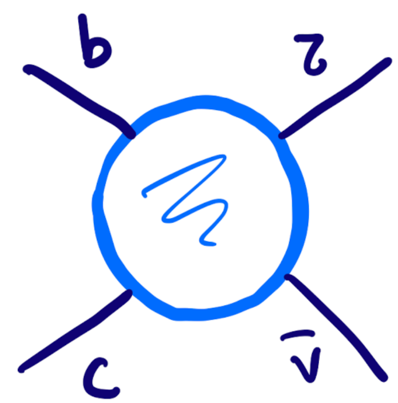
What do we know so far?

- What is the **scale of New Physics**? [Di Luzio et al. '17]
  - For perturbative couplings:

$$\Lambda_{R_{K^{(*)}}} \lesssim 30~\text{TeV}$$



$$\Lambda_{R_{D^{(*)}}} \lesssim 3~\text{TeV}$$



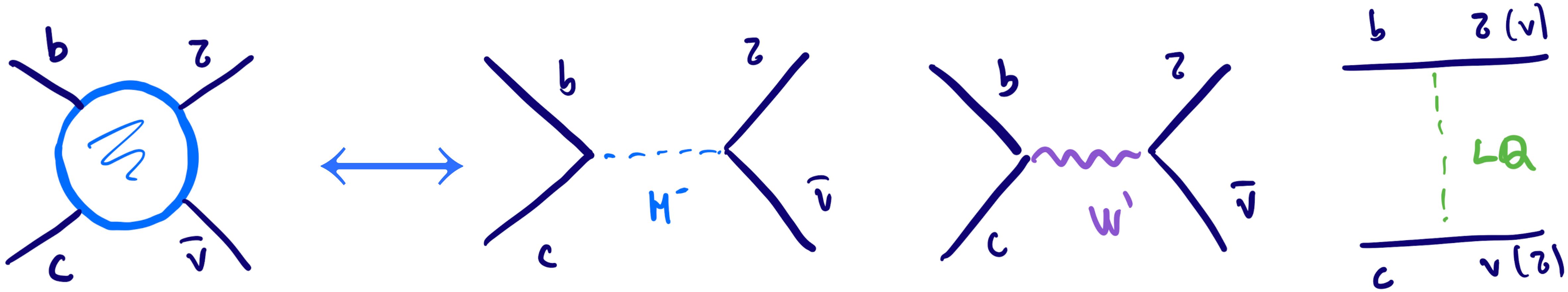
- Moreover, *good agreement* between theory and experiment in LFU tests with *K*-, *D*-meson and τ-lepton decays.

  ⇒ ***New Physics*** couplings to SM fermions must be **hierarchical**.

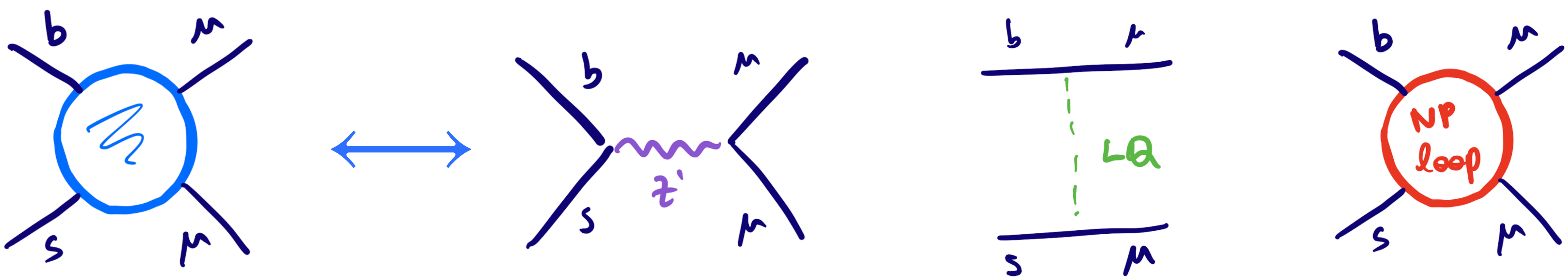
From EFTs to concrete models

Many papers in the literature...

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



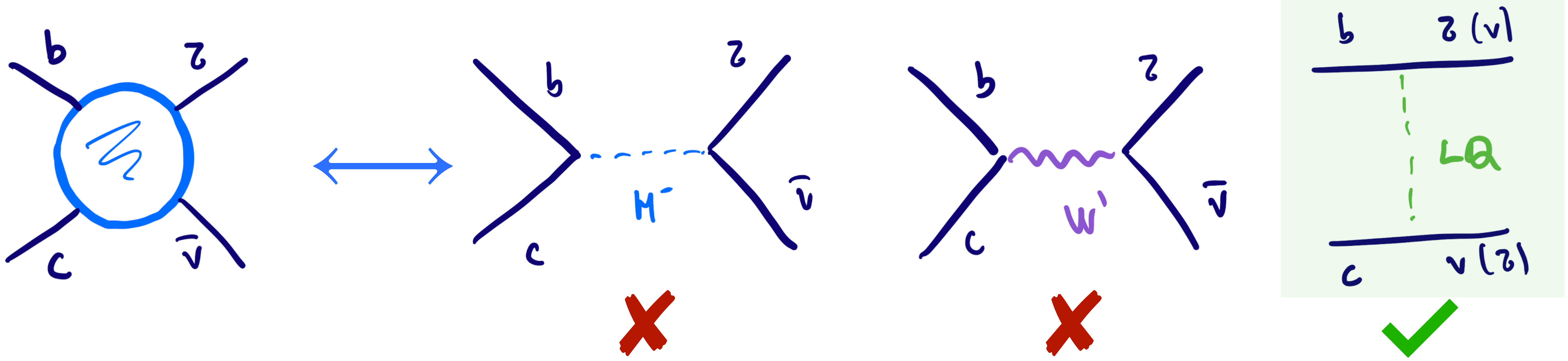
- $b \to s\ell\ell$:



From EFTs to concrete models

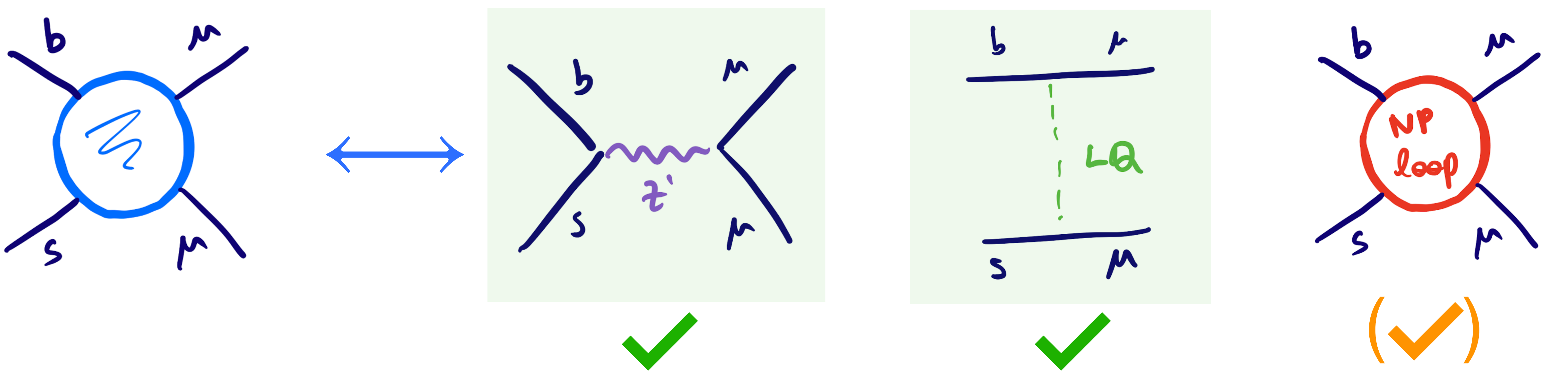
Many papers in the literature...

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



$(B_c$-meson lifetime$)$ $(\Delta F = 2, pp \to \tau\tau \ldots)$

- $b \to s\ell\ell$:



Challenging task because of the numerous exp. constraints: *flavor, LHC, EWPT...*

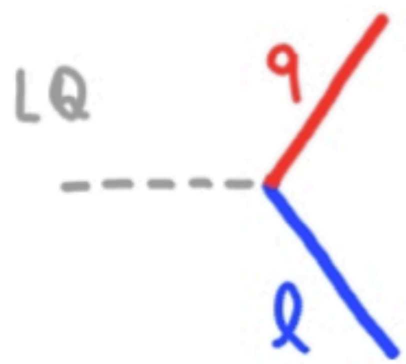
Which leptoquark?

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

[Buchmuller, Wyler. '88]

Few scenarios are viable!

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



	Model		$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
Spin 0	S_3	$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	✓	✗	✗
	S_1	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✗	✓	✗
	R_2	$(\mathbf{3}, \mathbf{2}, 7/6)$	✗	✓	✗
Spin 1	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 UV completion needed.
  - $\mathscr{G}_{\text{PS}} = SU(4) \times SU(2)_L \times SU(2)_R$ contains $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$

    See back-up!
  - Viable TeV models proposed: $U_1 + Z' + g'$ *(more than one mediator!)*

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

- Two scalar LQs are also viable:
  - S_1 & S_3 , or R_2 & S_3 .

[Becirevic et al. '18]

[Crivellin et al. '17, Marzocca '18]

From LFUV to high-p_T physics

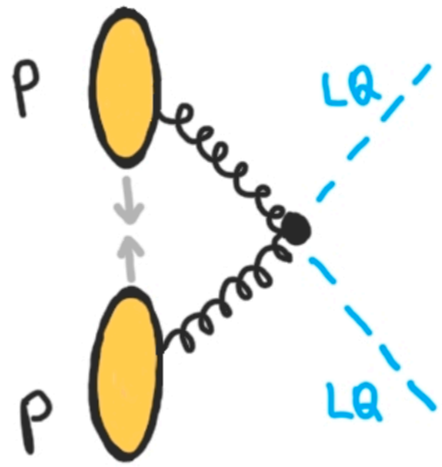
LHC constraints

See talk by K. Yong Sheng!

i. LQ pair-production

Production dominated by QCD:

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



$+ \ \dots$

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

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

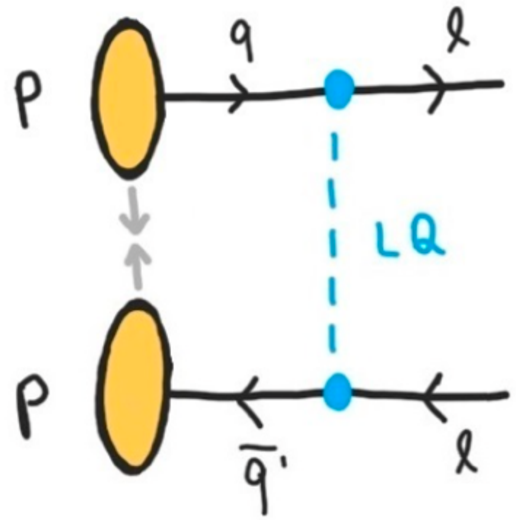
Decays	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\text{int}}$ / Ref.
$jj\,\tau\bar{\tau}$	–	–	–
$b\bar{b}\,\tau\bar{\tau}$	1.0 (0.8) TeV	1.5 (1.3) TeV	36 fb^{-1} [39]
$t\bar{t}\,\tau\bar{\tau}$	1.4 (1.2) TeV	2.0 (1.8) TeV	140 fb^{-1} [40]
$jj\,\mu\bar{\mu}$	1.7 (1.4) TeV	2.3 (2.1) TeV	140 fb^{-1}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

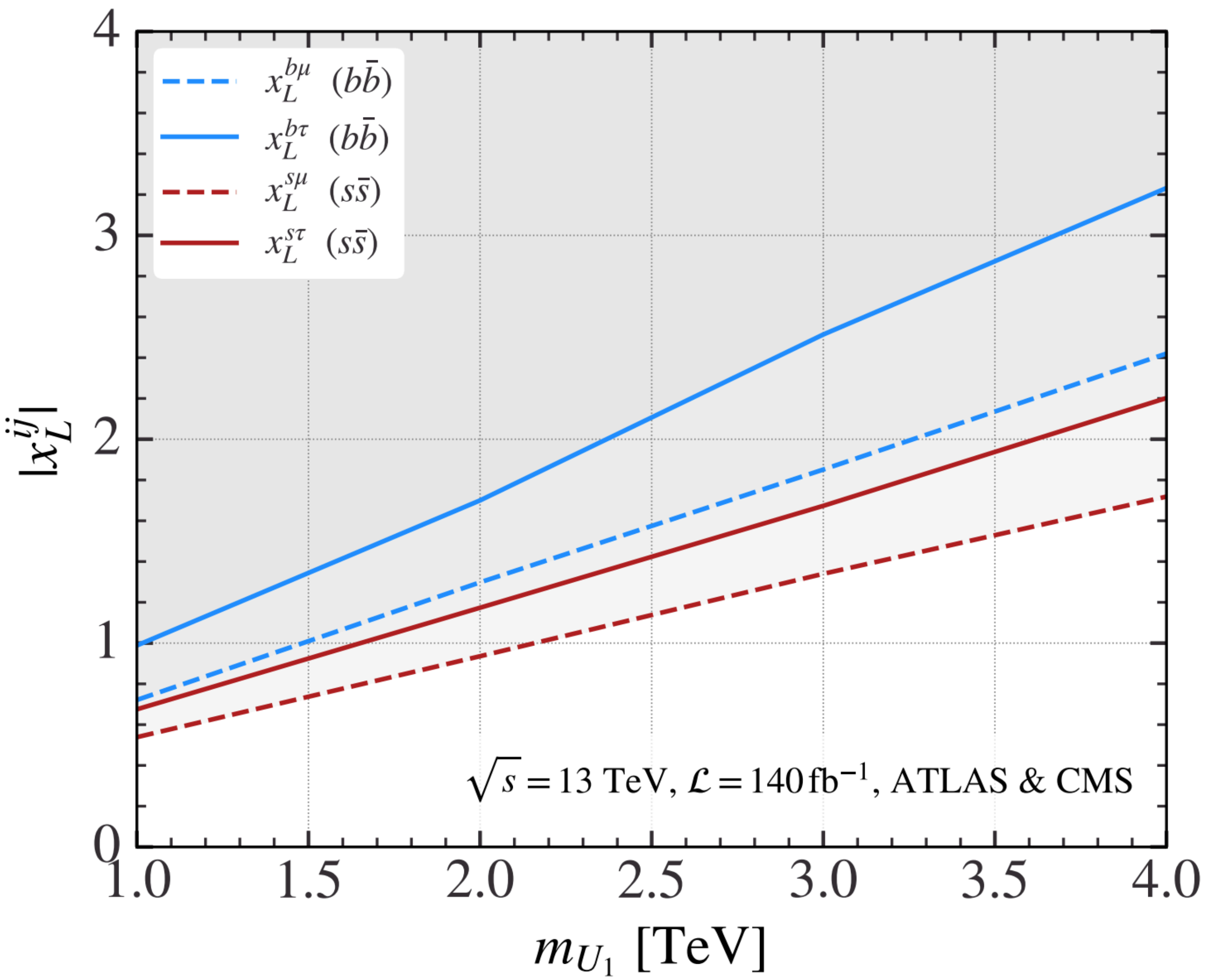
[Angelescu, Becirevic, Faroughy, Jaffredo, **OS**. '21]

LHC constraints

ii. Di-lepton production at high-p_T

Useful upper limits on LQ couplings:





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

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

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

First considered by [Eboli, '88]

High-p_T package

[Allwicher, Faroughy, Jaffredo, **OS**, Wilsch. 2204.XXXXX]

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<<HighPT`
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HighPT : High-p_T Tails

Authors : Lukas Allwicher, Darius A. Faroughy, Florentin Jaffredo, Olcyr Sumensari, and Felix Wilsch

Reference : arXiv:22xx.xxxxx

Website : https://github.com/HighPT/HighPT

HighPT is free software under the terms of the MIT License.

Please submit bugs and feature requests using GitHub's issue system at:

https://github.com/HighPT/HighPT/issues

Recast of LHC searches for the SMEFT and simplified scenarios

$pp \to \tau\tau$	[arXiv:2002.12223]
$pp \to ee,\ \mu\mu$	CMS-PAS-EXO-19-019
$pp \to \tau\nu$	ATLAS-CONF-2021-025
$pp \to e\nu,\ \mu\nu$	[arXiv:1906.05609]
$pp \to e\mu,\ e\tau,\ \mu\tau$	CMS-PAS-EXO-19-014

High-p_T package

[Allwicher, Faroughy, Jaffredo, **OS**, Wilsch. 2204.XXXXX]

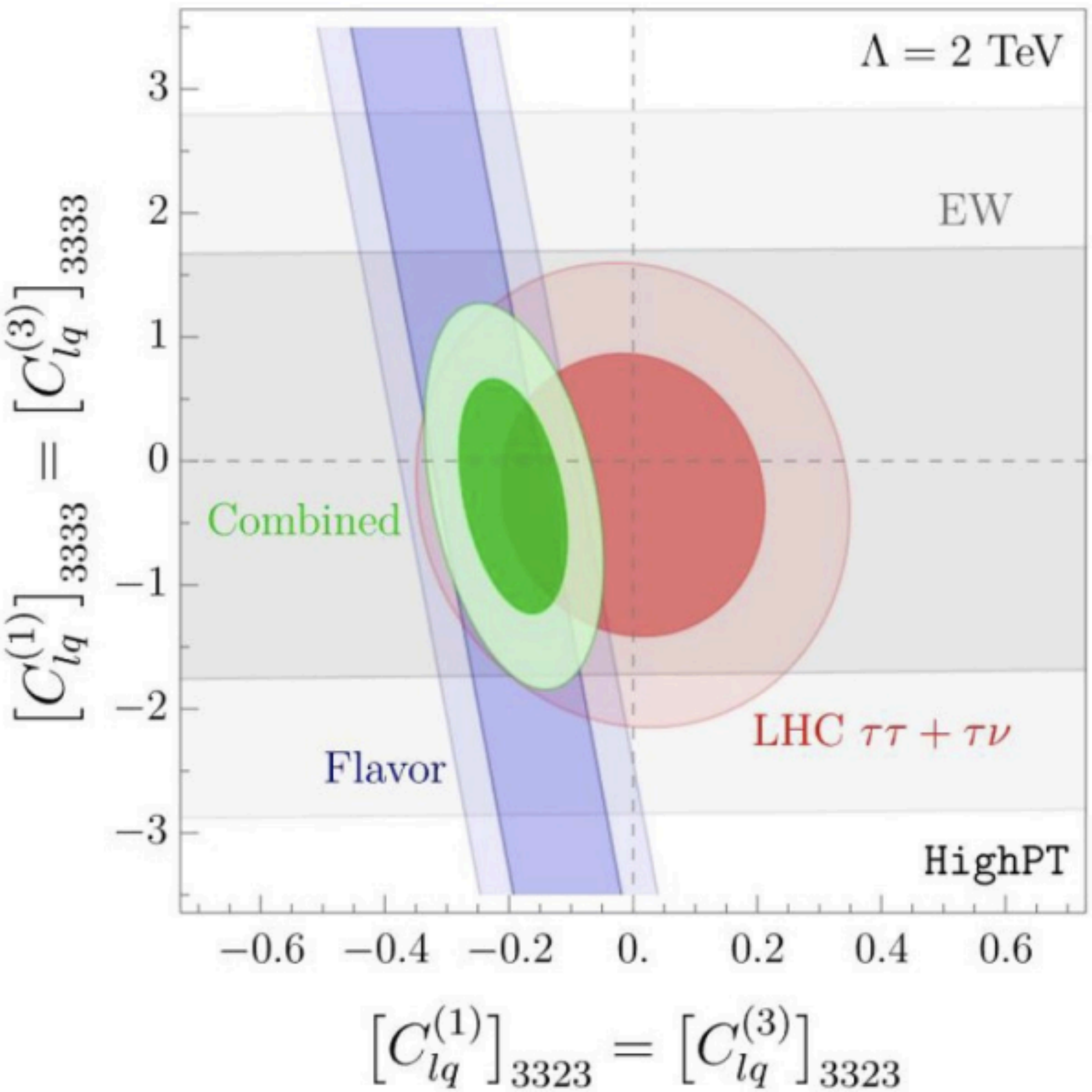
Example: SMEFT

Effective operators predicted by the $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$ leptoquark:

$$\left[C_{lq}^{(1)}\right]_{ijkl} = \left(\bar{L}_i \gamma^\mu L_j\right)\left(\bar{Q}_k \gamma_\mu Q_l\right)$$

$$\left[C_{lq}^{(3)}\right]_{ijkl} = \left(\bar{L}_i \gamma^\mu \tau^I L_j\right)\left(\bar{Q}_k \gamma_\mu \tau^I Q_l\right)$$

High-p_T constraints are needed to remove the flat direction!



Predictions at low-energies

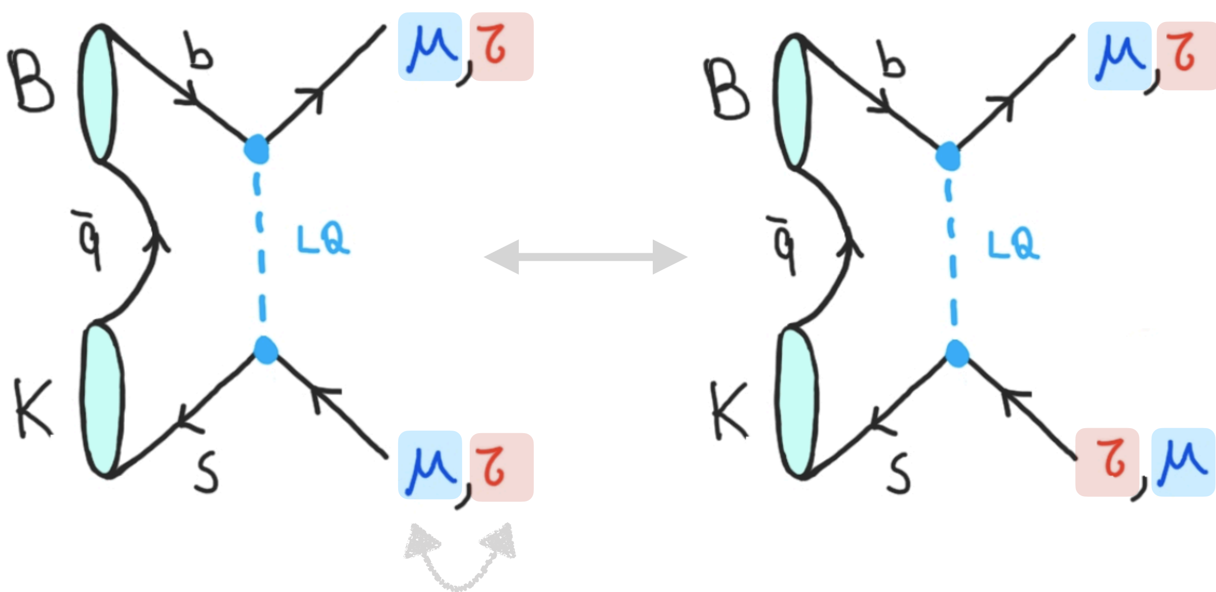
- LFV in B-decays
- B-decays with missing energy

Lepton Flavor Violation

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

see also [Glashow et al. '14]

- **LFU**V ↔ **LFV**:



Predictions for

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

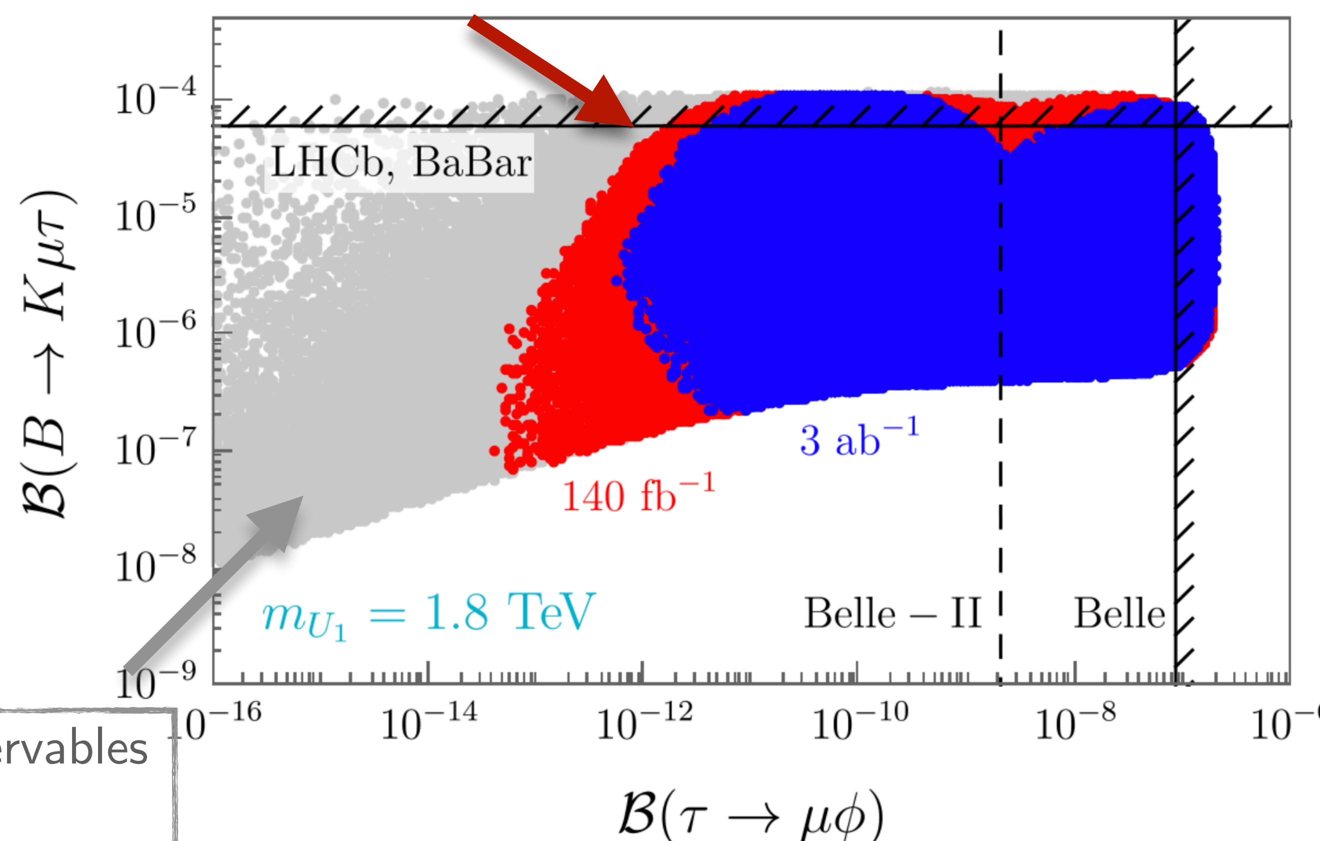
New searches (95% CL): [LHCb]

$$\mathcal{B}(B_s \to \mu\tau)^{\text{exp}} < 4.2 \times 10^{-5}$$
$$\mathcal{B}(B \to K^{(*)}\mu\tau)^{\text{exp}} < 4.5 \times 10^{-5}$$

LHC constraints

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

High-p_T constraints set lower bounds on $\mathcal{B}(B \to K\mu\tau)$!



Several flavor observables (at tree-level)

B-decays with missing energy

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

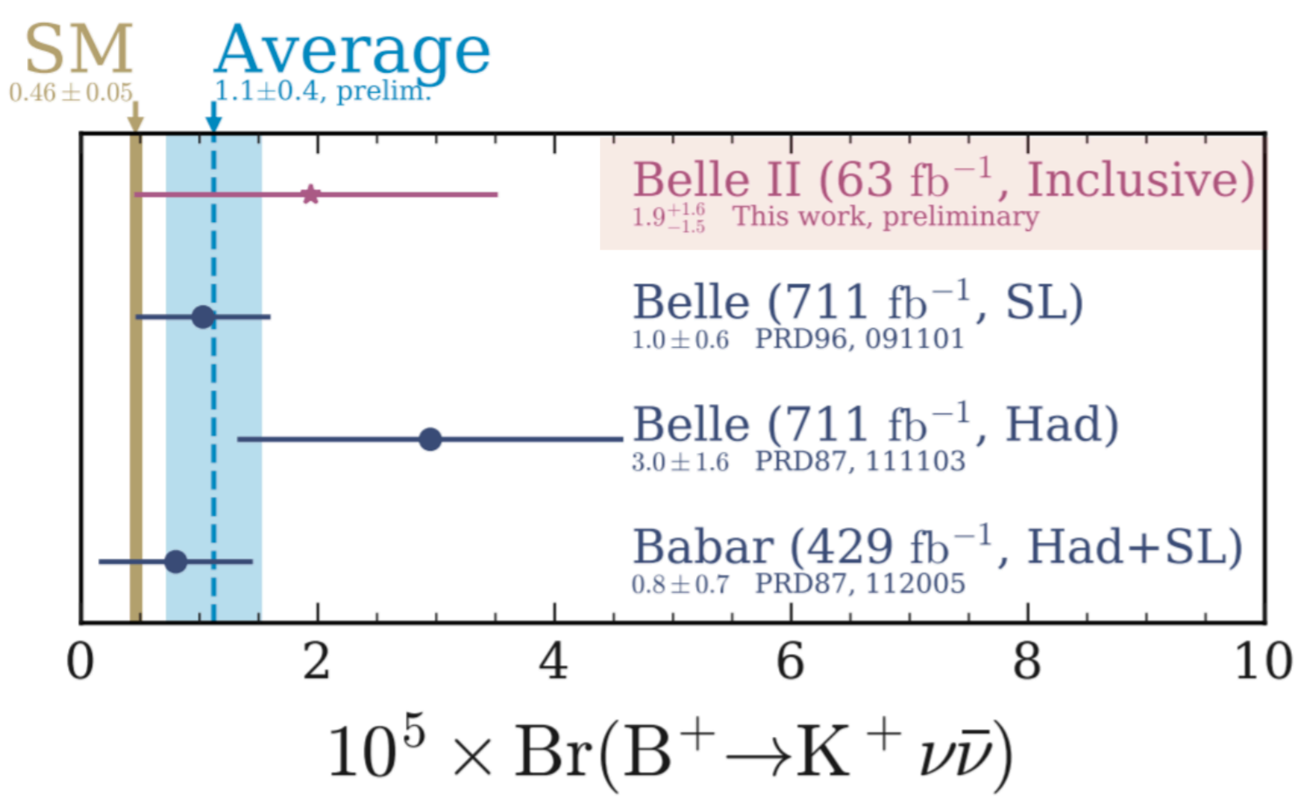
- **Clean observable** in the SM:

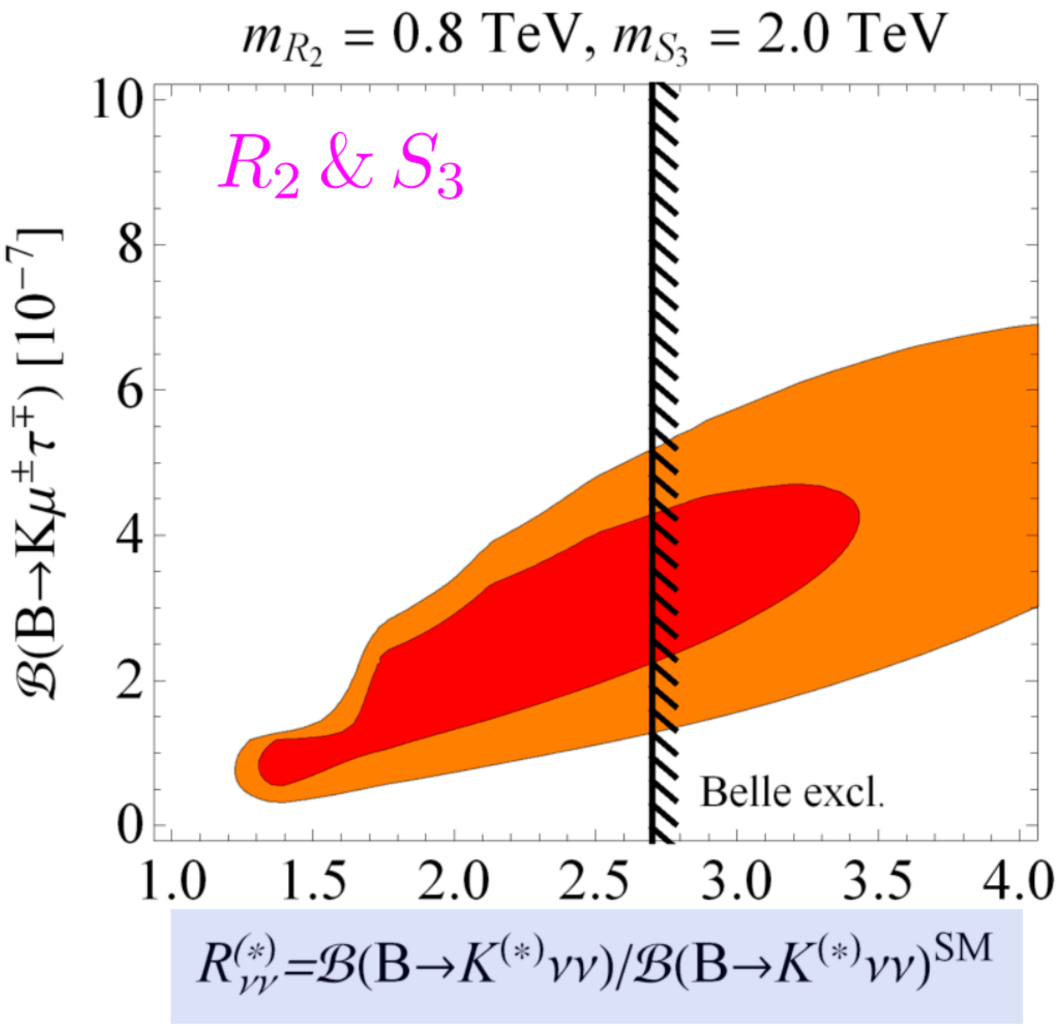
$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})^{\rm SM} = 4.6(5) \times 10^{-6}$$

[Buras et al. '14, Blake et al. '16]

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

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





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

Summary and perspectives

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

  Wait for Belle-II for an independent cross-check!

- We identified the mediators that can explain $R_{K^{(*)}}$ and/or $R_{D^{(*)}}$.

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

- There is a pronounced complementarity of flavory-physics constraints with those obtained from high-p_T searches at the LHC.

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

- Many upcoming low-energy measurements will be fundamental to refute or confirm the remaining viable models.

  $R_{D^{(*)},D_s^{(*)},\Lambda_c^{(*)},\ldots}$ $\quad R_{K^{(*)},\phi,\ldots}$ $\quad B \to K^{(*)}\mu\tau$ $\quad B \to K^{(*)}\nu\bar{\nu}$ $\quad \ldots$

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

Data-driven model building!

Thank you!

Back-up

SM predictions

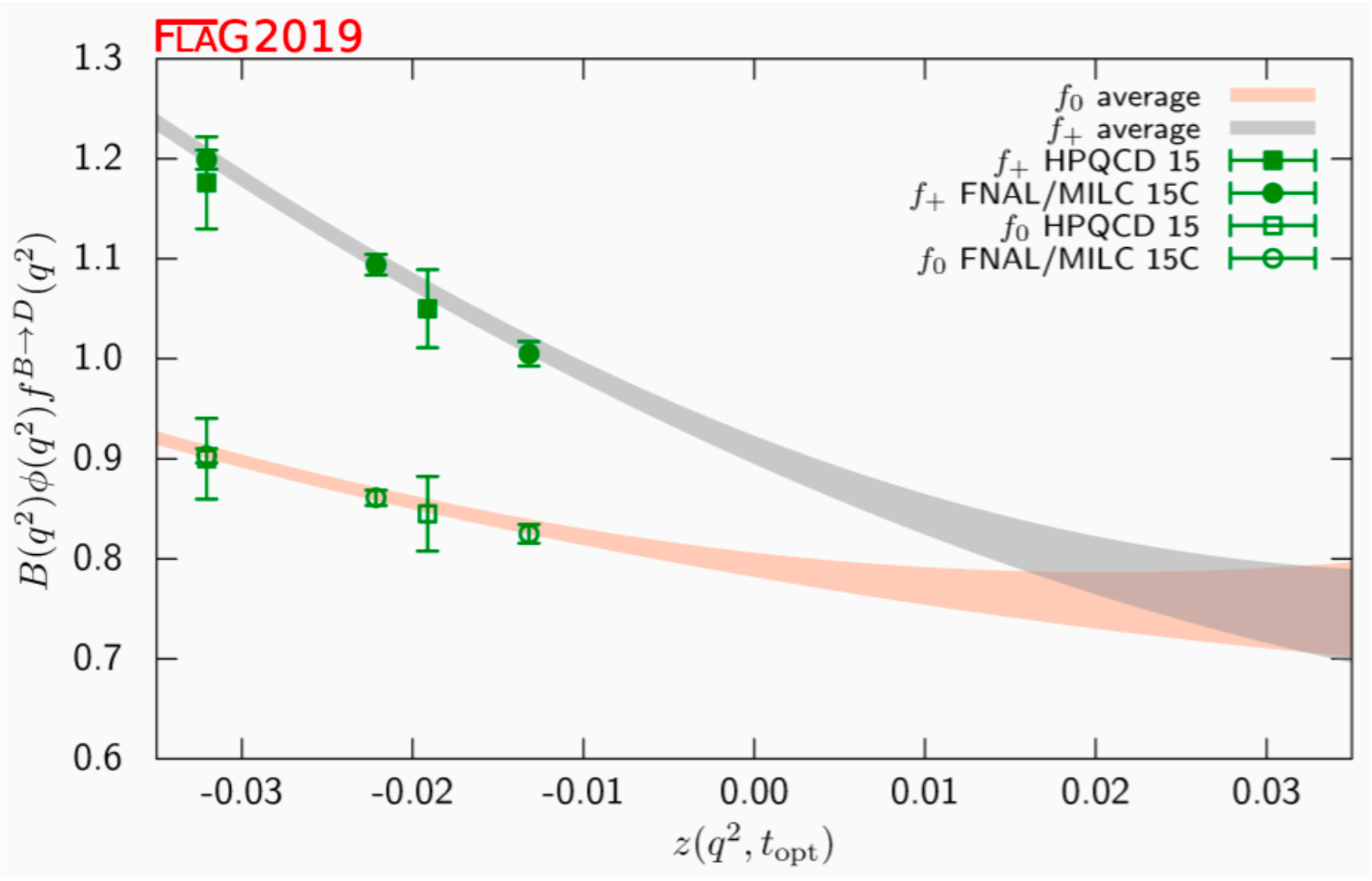
Form-factors: R_D

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

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

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

[MILC/Fermilab '15, HPQCD '15]



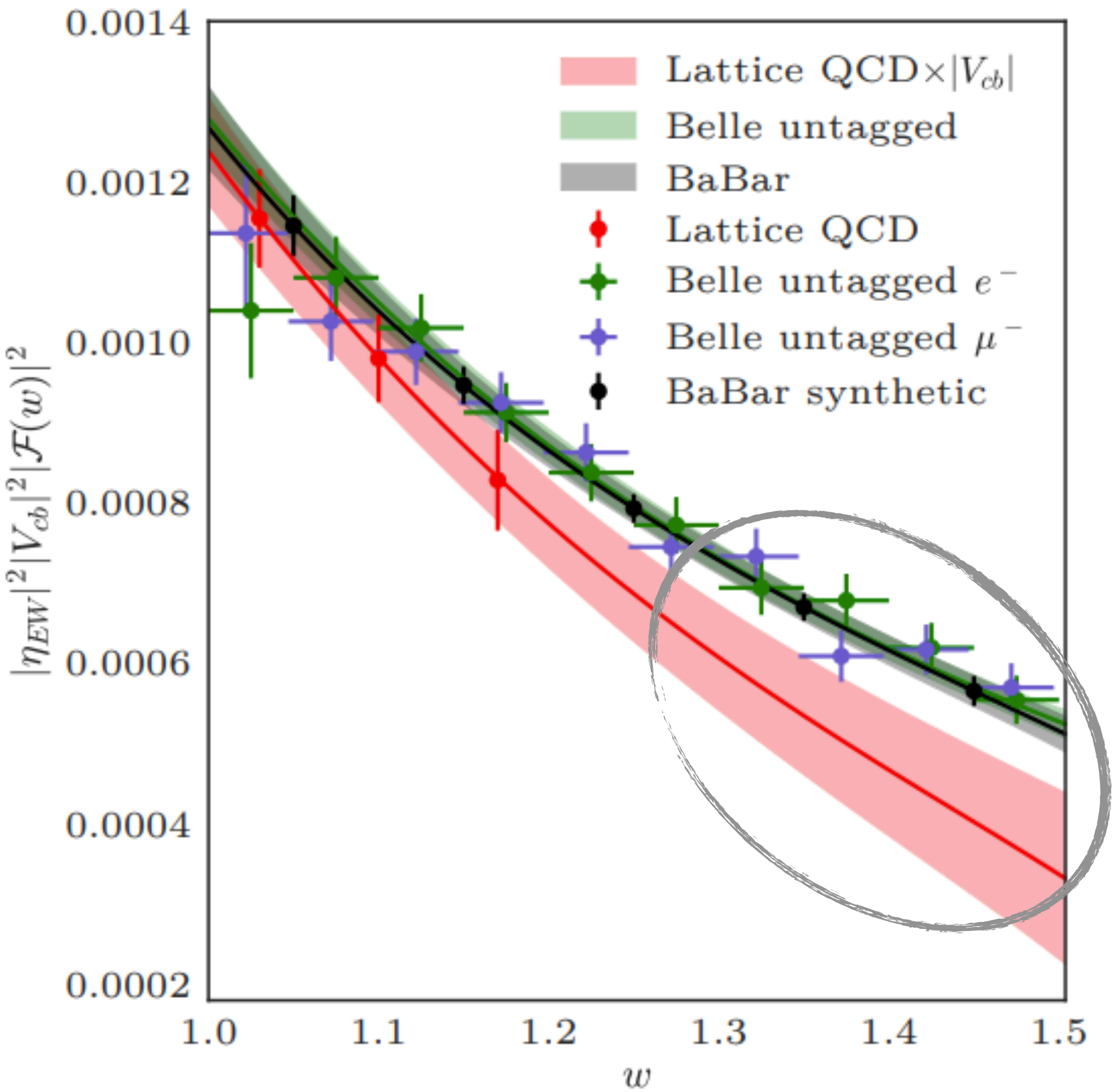
[FLAG' 21] average:

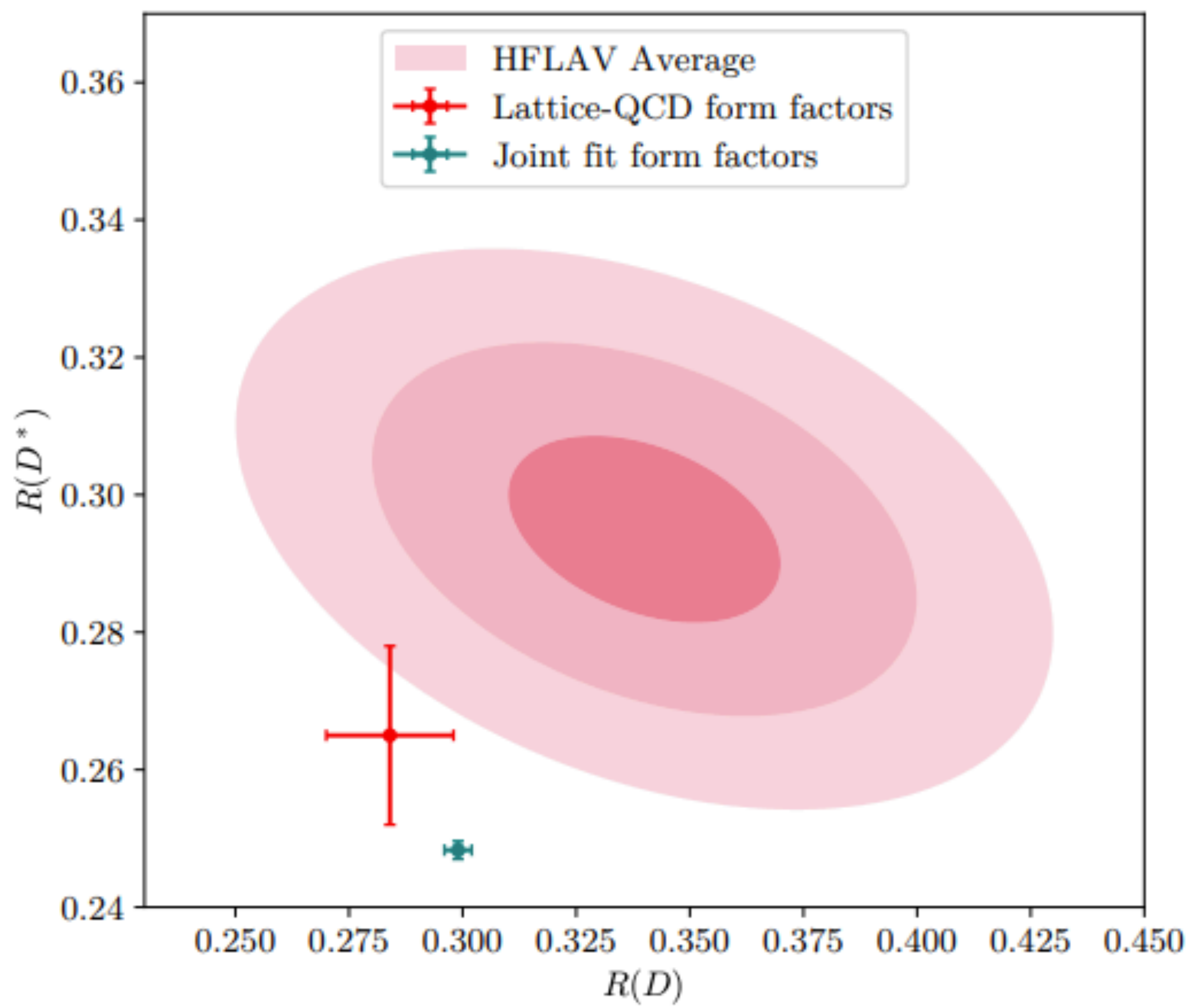
$$R_D^{\text{SM}} = 0.300(10)$$

Warning!

[MILC/Fermilab, 2105.14019]

$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^*\ell\nu) \propto |V_{cb}|^2 \, |\mathcal{F}(w)|^2 \qquad \left[w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}} \right]$$





[Intermezzo] How to improve the SM prediction for R_{D^*} ?

- Theory uncertainties are related to m_τ, i.e the only source of LFU breaking in the SM:

$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B\to D^*\ell\bar\nu) = \Phi(q^2)\,\omega_\ell(q^2)\left[H_V(q^2)^2 + \frac{m_\ell{}^2}{m_\ell{}^2+2q^2}H_S(q^2)^2\right]$$

H_V: $\propto A_1(q^2),\; A_2(q^2),\; V(q^2)$ $\qquad$ H_S: $\propto A_0(q^2)$

(see back-up)

- A **simple redefinition** can reduce these uncertainties:

$$R_{D^*}^{(\tau/\mu)} = \frac{\int_{m_\tau^2}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B\to D^*\tau\bar\nu)}{\int_{m_\mu^2}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B\to D^*\mu\bar\nu)} \quad\longrightarrow\quad R_{D^*}^{(\tau/\mu)}[q^2_{\min}] = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B\to D^*\tau\bar\nu)}{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B\to D^*\mu\bar\nu)}$$

	Observable	Latt.	Latt. +Exp
Usual definition →	R_{D^*}	0.27(1) [5%]	0.248(1) [0.5 %]
Definition with same bins →	$R_{D^*}[m_\tau^2]$	0.343(6) [2%]	0.337(1) [0.4%]
	$R_{D^*}[5\ \mathrm{GeV}^2]$	0.422(3) [0.5 %]	0.422(1) [0.2%]

[Isidori, **OS**. '20]

NB. Re-weighting of the muon rate by $\omega_\tau(q^2)/\omega_\mu(q^2)$ can further reduce the theory uncertainties.

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]

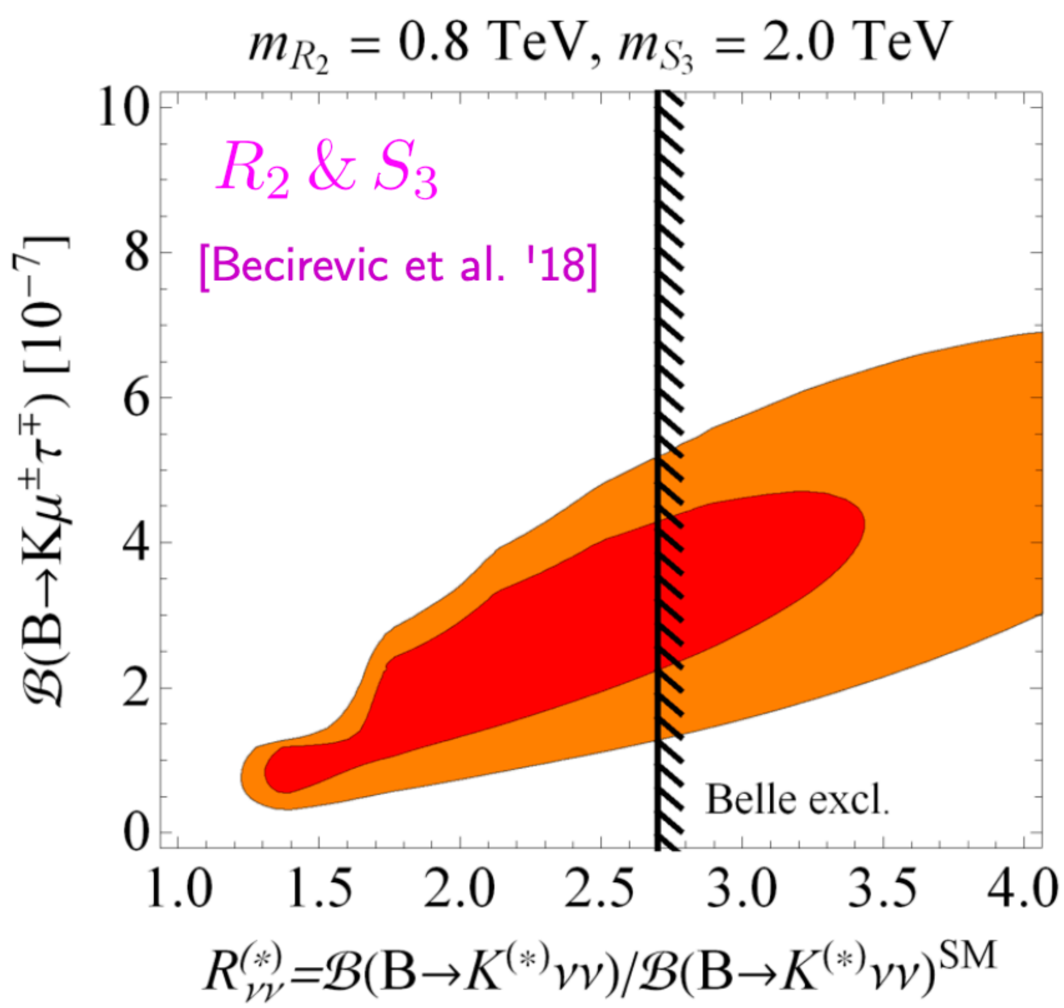
- $SU(4) \times SU(3)' \times SU(2)_L \times U(1)' \to \mathcal{G}_{\rm SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$
- Flavor violation from (ad-hoc) mixing with vector-like fermions.
- Main feature: $U_1 + Z' + g'$ at the TeV scale.

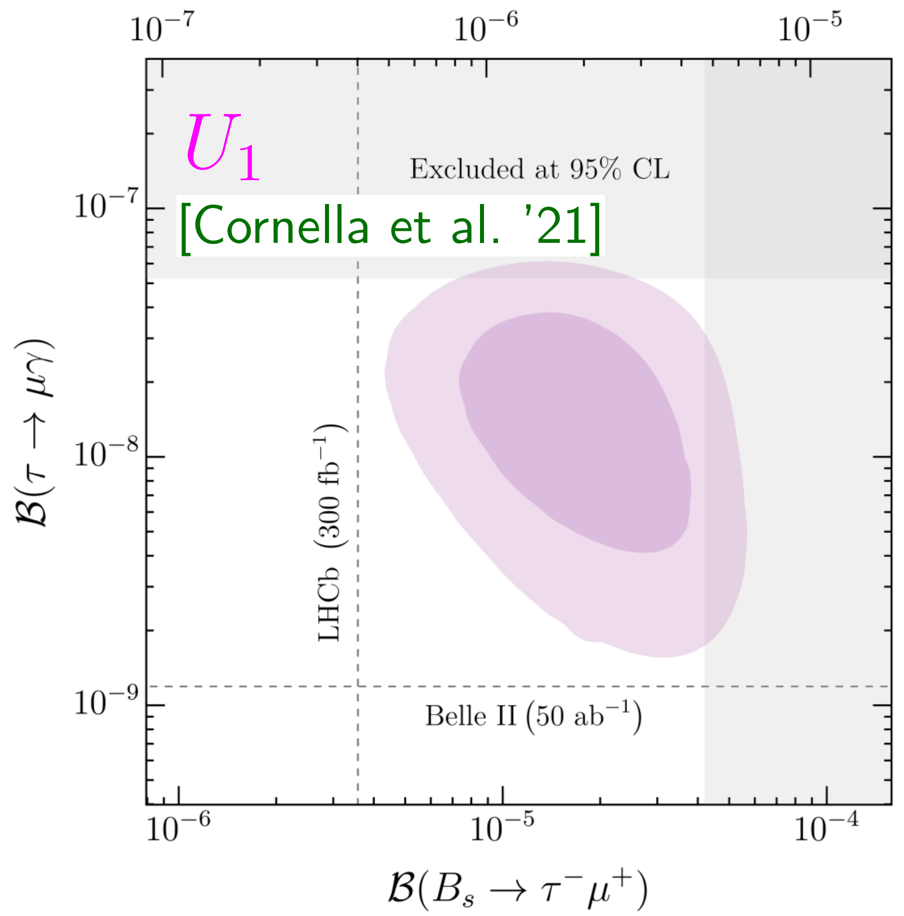
Rich LHC pheno, cf. [Baker et al. '19], [Di Luzio et al. '18]

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)!

Large contributions to $b \to s\mu\tau$ is a **prediction** of the **minimalistic solutions** to the ***B*-physics anomalies**.





EFT predictions:

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

i. LH operators:

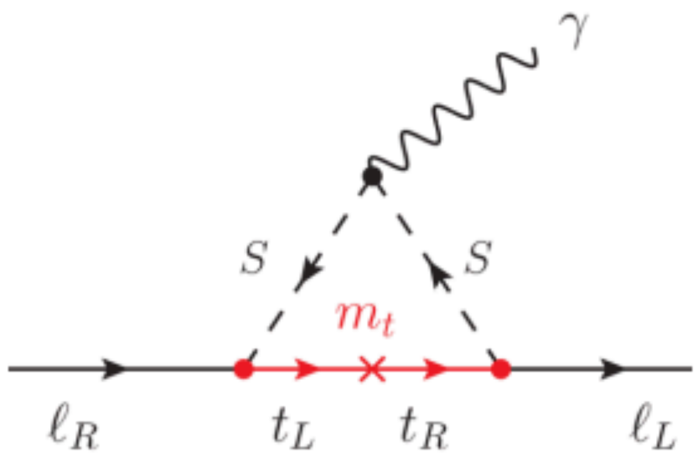
$$\frac{\mathcal{B}(B_s \to \mu\tau)}{\mathcal{B}(B \to K\mu\tau)} \simeq 0.8\,, \quad \frac{\mathcal{B}(B \to K^*\mu\tau)}{\mathcal{B}(B \to K\mu\tau)} \simeq 1.8$$

ii. Scalar operators:

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

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	$(\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	$\overline{Q}^C L$	-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
$\widetilde{S}_1$	$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	$\overline{d}_R^C e_R$	-2
S_1	$(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	$\overline{Q}^C L$, $\overline{u}_R^C e_R$	-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} (?) .

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...)