Phenomenology of flavor anomalies

Olcyr Sumensari

IJCLab (Orsay)

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Outline

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

See also:

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

R_{pK}

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

$R_{J/\psi}$

[LHCb, *B-factories*]

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

This talk:

i. LFU in the SM: Current status
ii. New Physics interpretations (EFT and beyond)
iii. Connection to Δa_μ ?
iv. Implications

Lepton Flavor Universality

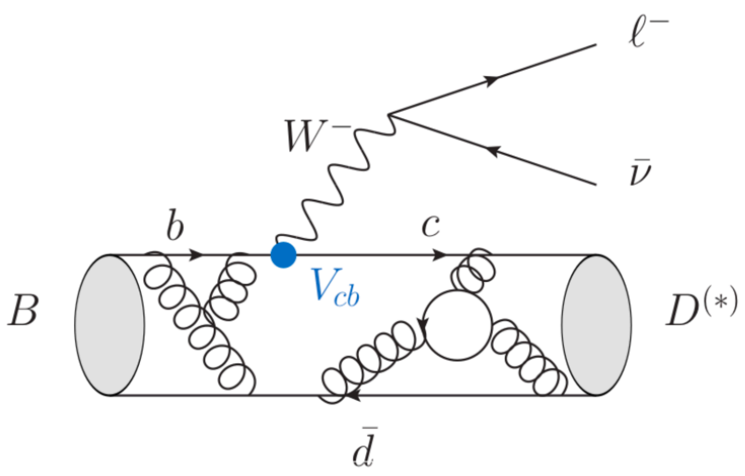
R_D and R_{D^*}: current status

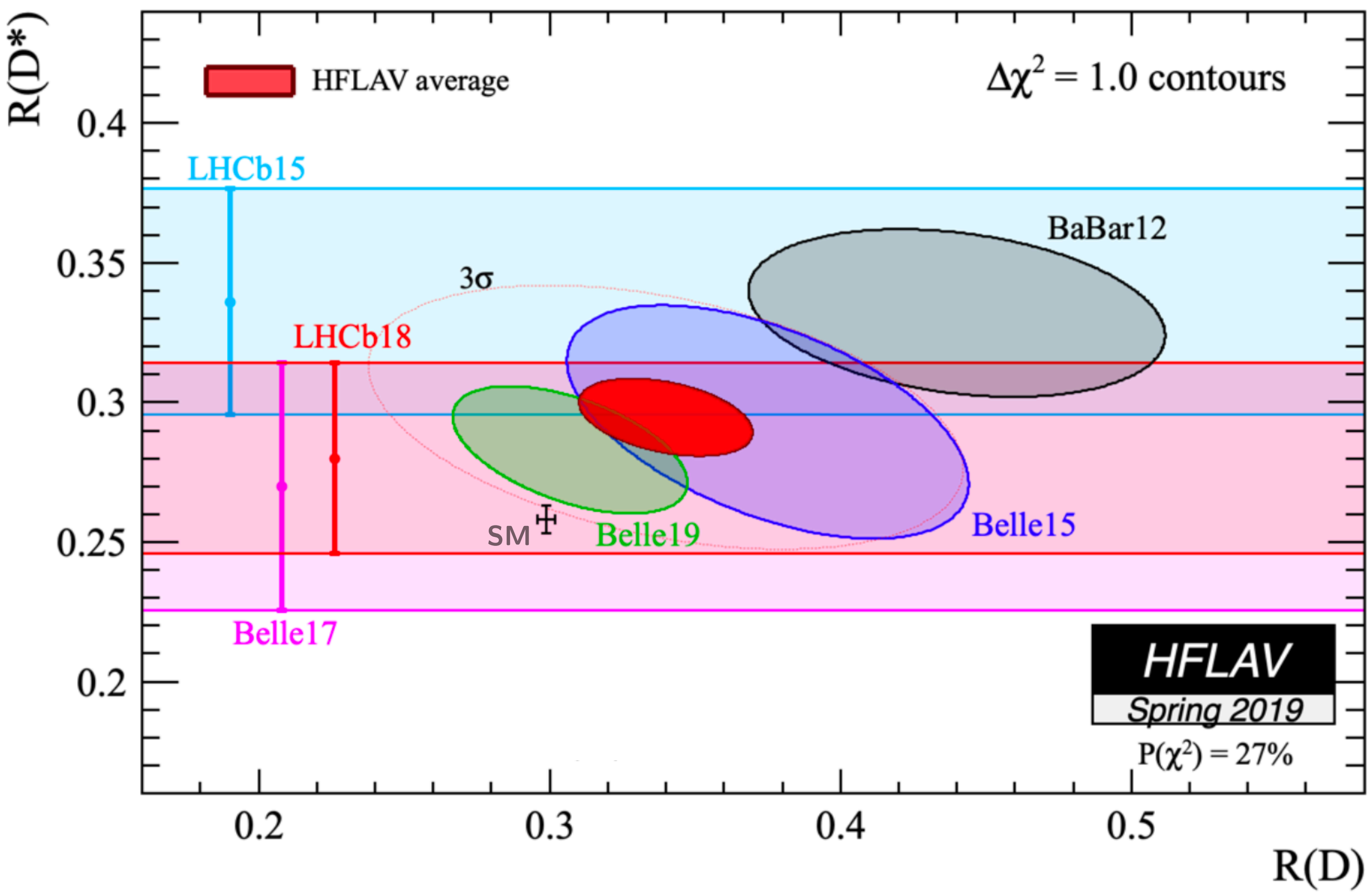
LFU in $b \to c\tau\bar{\nu}$

See talks by G. De Nardo, T. Bowcook

Experiment

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

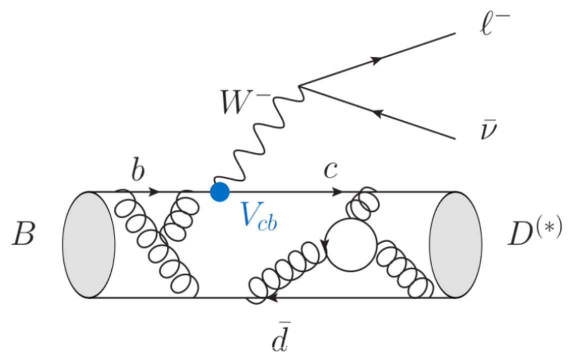




- R_D^{exp} and $R_{D^*}^{\text{exp}}$: **dominated by BaBar!**

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

SM predictions: $B \to D^{(*)}\ell\bar{\nu}$



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...)

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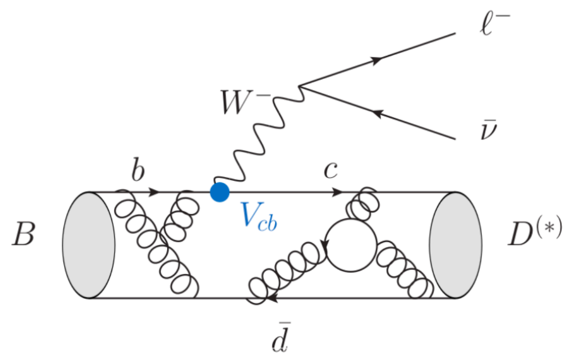

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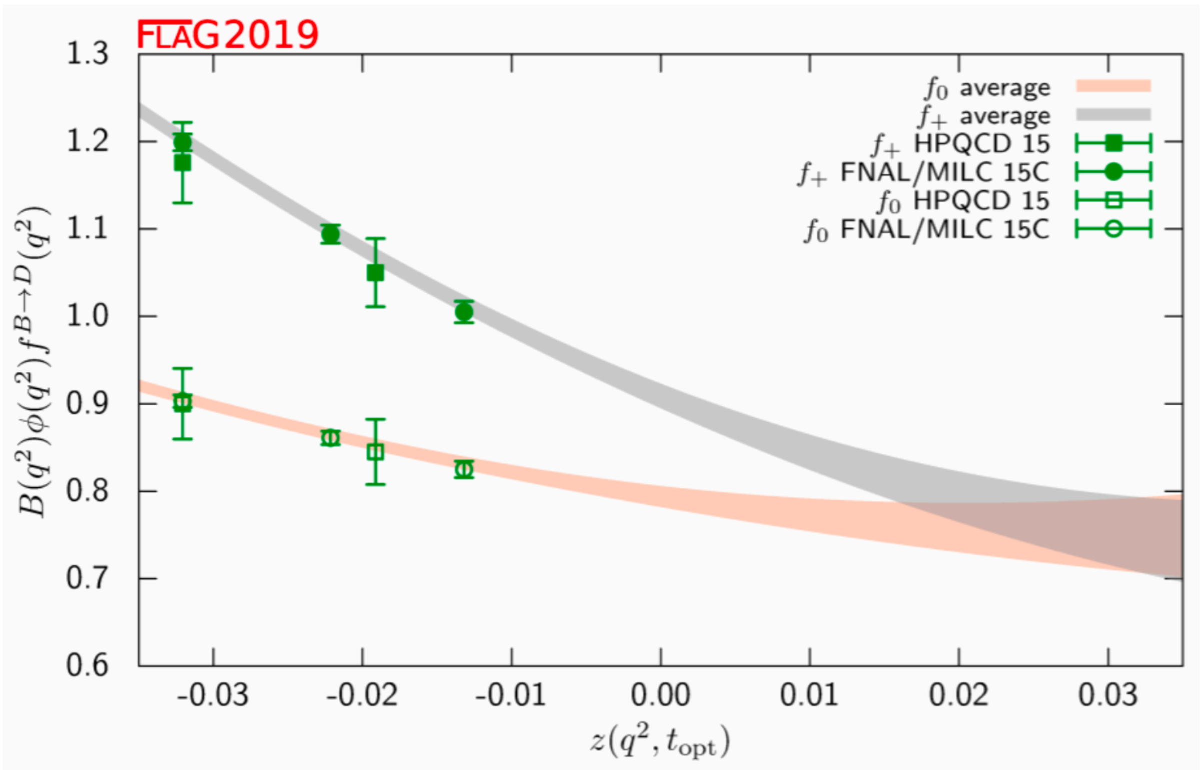
For light (heavy) leptons:

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

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

$$R_D^{\mathrm{latt.}} = 0.293(5)$$

[FLAG '21]



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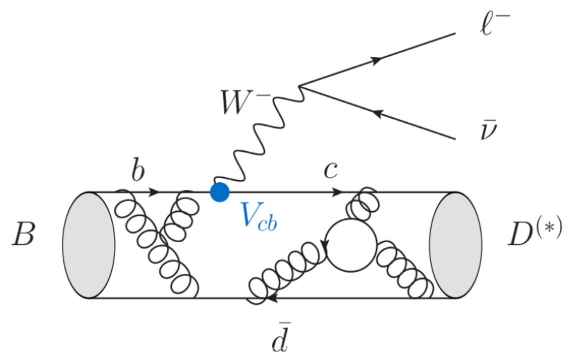

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$$R_D^{\text{latt.}} = 0.293(5) \qquad R_D^{\text{latt.+exp}} = 0.295(3)$$

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

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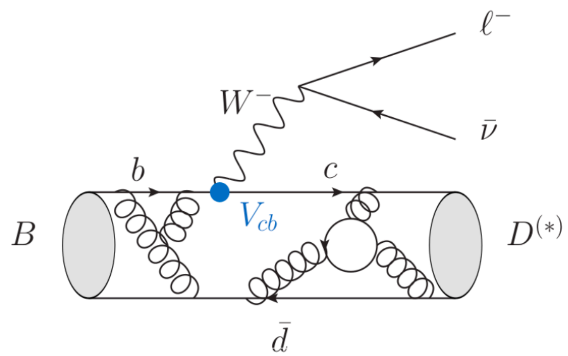

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$B \to D^{(*)} l\bar{\nu} \quad (l = e, \mu)$

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

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

$R_{D^*}^{\text{latt.}} = 0.265(13)$ $\quad$ $R_{D^*}^{\text{latt.+exp}} = 0.2483(13)$

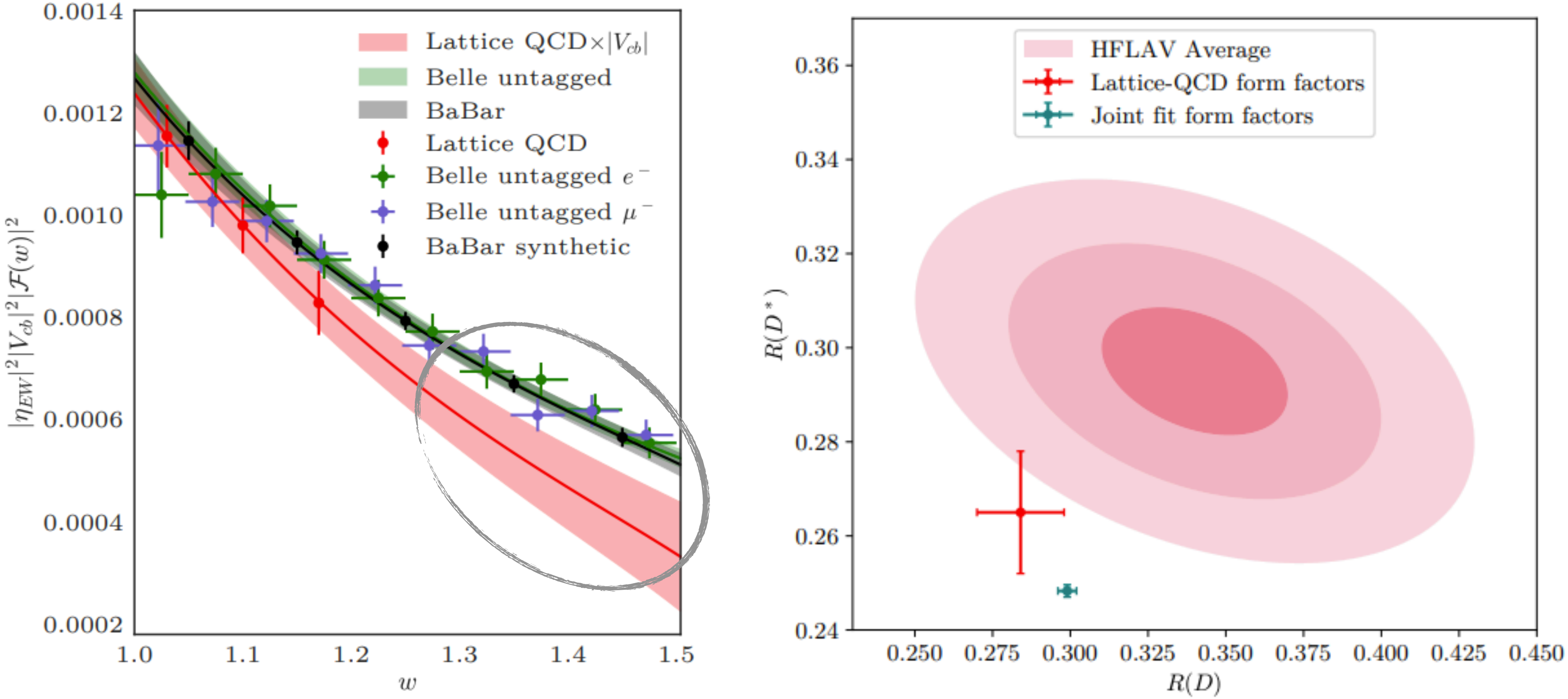
1.3σ apart ⚠

NB. Soft-photon corrections: first steps in [de Boer et al. '18]. More work needed (structure dependent terms?)

Warning!

[MILC/Fermilab, 2105.14019]

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



Way out: independent LQCD results + Belle-II!

How to improve our predictions?

- Th. uncertainties are related to m_τ (only source of LFU breaking in the SM):

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

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

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- A **simple redefinition** can reduce these uncertainties: [Ligeti et al. '16]

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

	Observable	Latt. (FNAL)
Usual definition →	R_{D^*}	$0.27(1)$ $[5\,\%]$
Definition with same bins →	$R_{D^*}[m_\tau^2]$	$0.343(6)$ $[2\,\%]$

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

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Definition with same bins →	$R_{D^*}[m_\tau^2]$	$0.343(6)$ $[2\,\%]$
Definition with same bins and re-weighting →	$\widetilde{R}_{D^*}[m_\tau^2]$	$1.080(4)$ $[0.4\,\%]$

NB. QED corrections not included!

EFT description of R_D and R_{D^*}

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

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

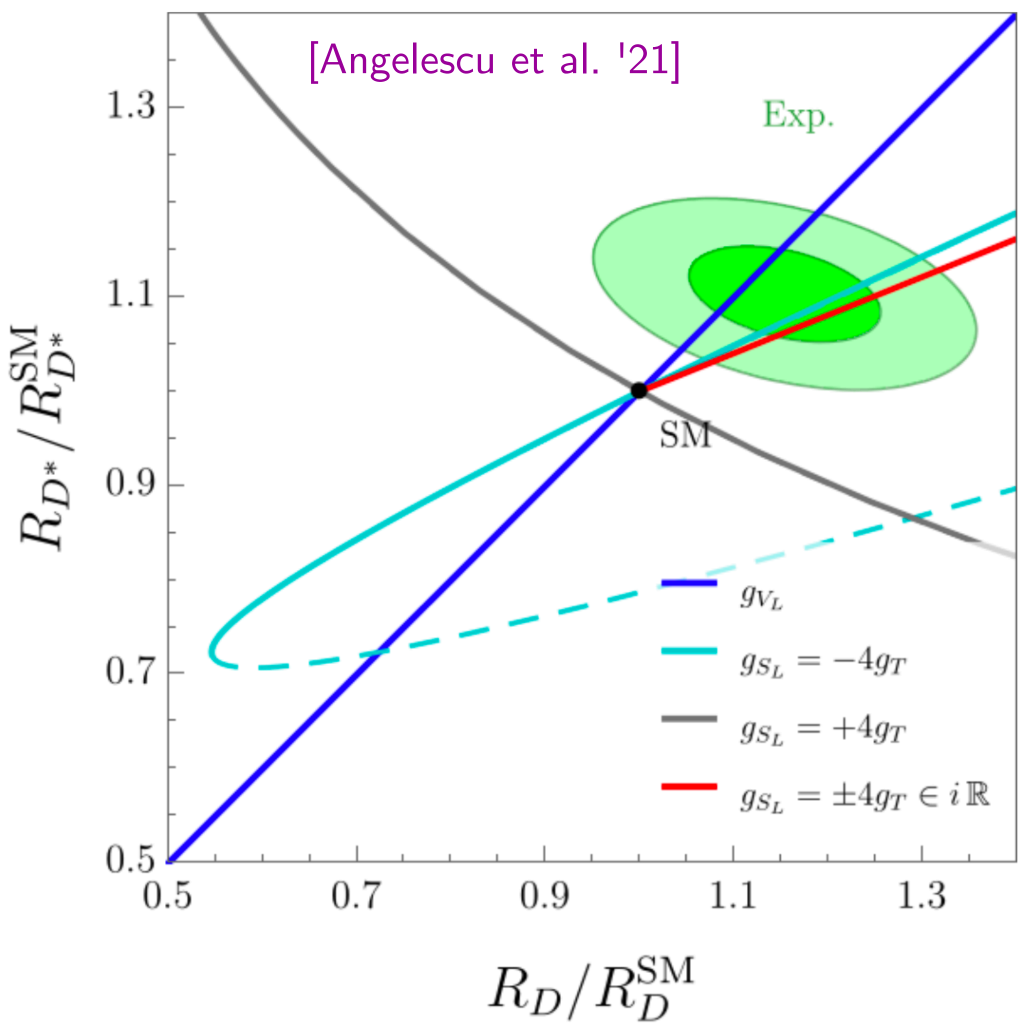
- $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge invariance:
  - $\Rightarrow$ g_{V_R} is LFU at dimension 6
  - $\Rightarrow$ Four coefficients left: g_{V_L} , g_{S_L} , g_{S_R} and g_T
- Several viable explanations of $R_{D^{(*)}}$:
  - $\Rightarrow$ e.g., $g_{V_L} = 0.07 \pm 0.02$, **but not only**!

[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?



- Several scenarios can accommodate data:

  $\Rightarrow$ *e.g.*, g_{V_L} and $g_{S_L} = \pm 4 g_T$ (at $\mu \approx 1$ TeV).

- More **exp. information** is **needed!**

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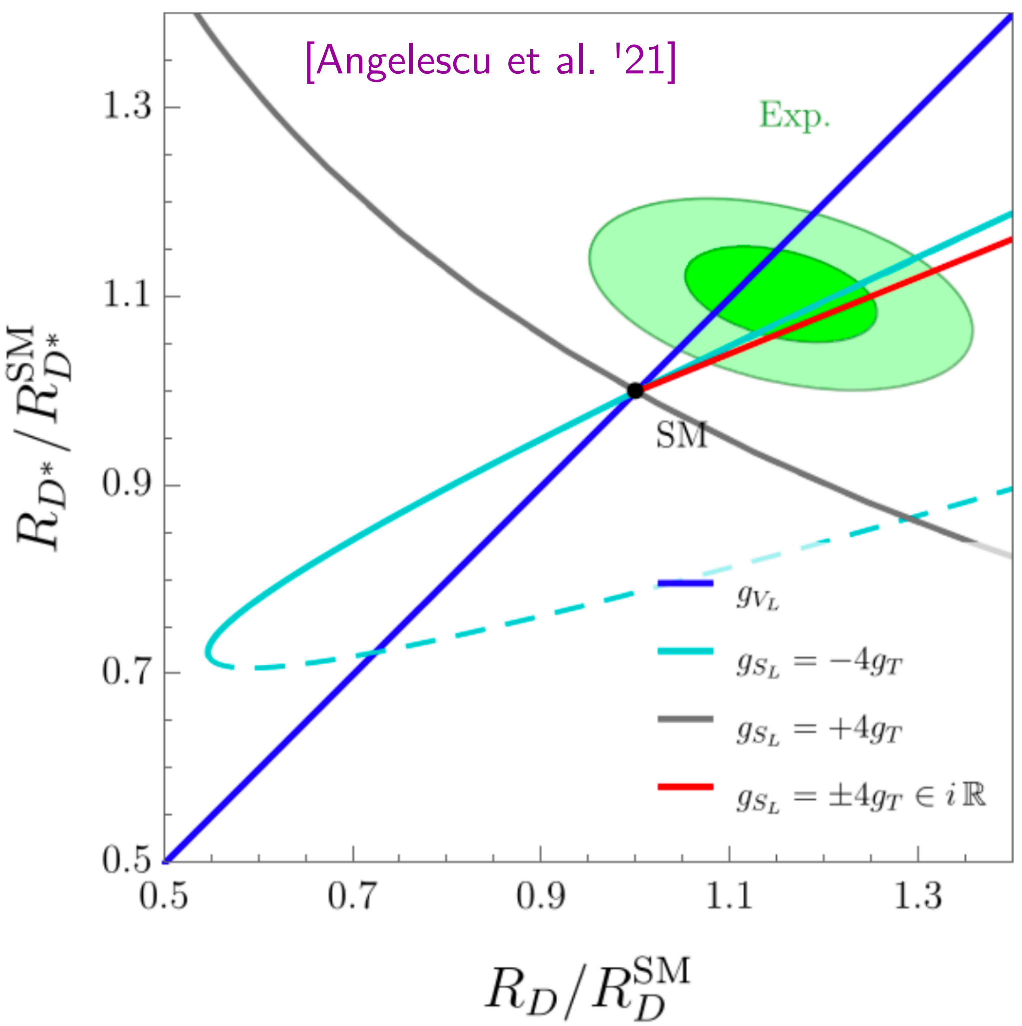

[Becirevic, Jaffredo, Peñuelas, **OS**. '21]

See also [Alonso et al. '18], [Becirevic et al. '19], [Murgui et al. '19], [Becirevic, Jaffredo. '22] ...

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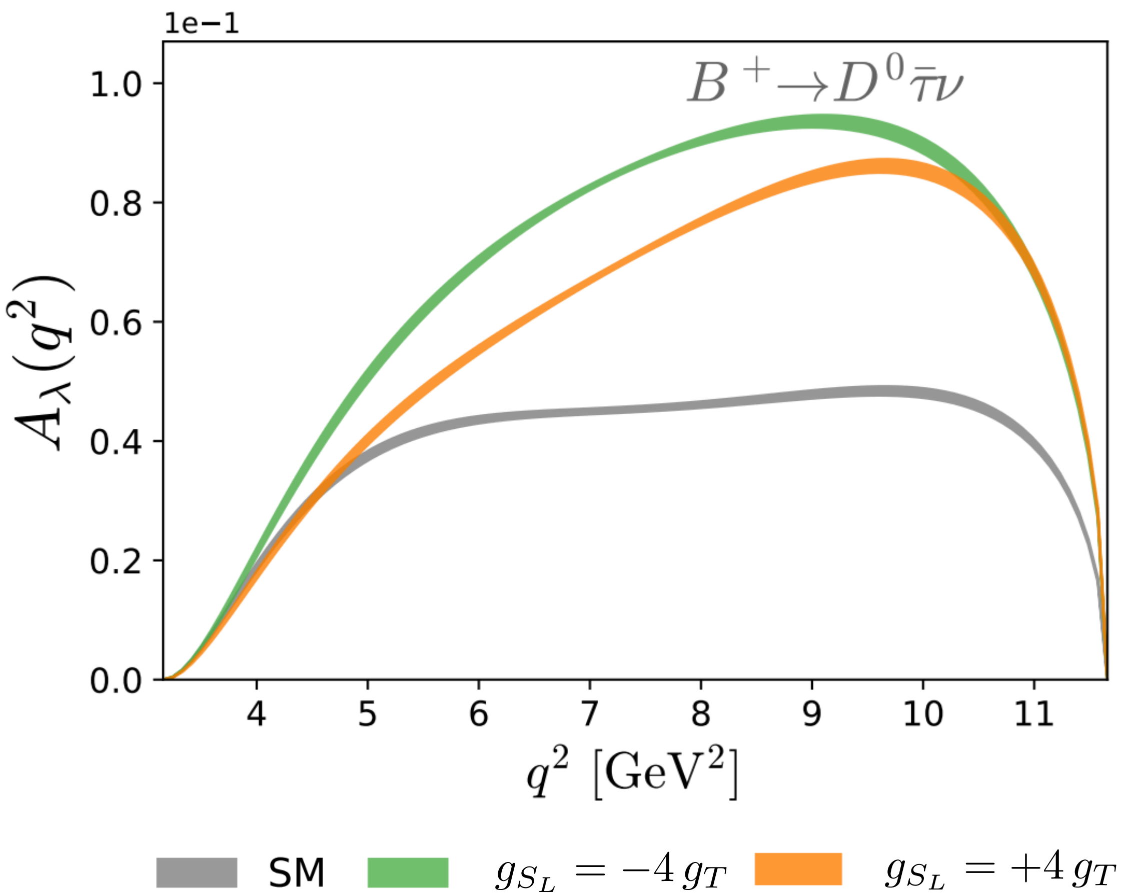
  i) *e.g., many angular observables:*

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



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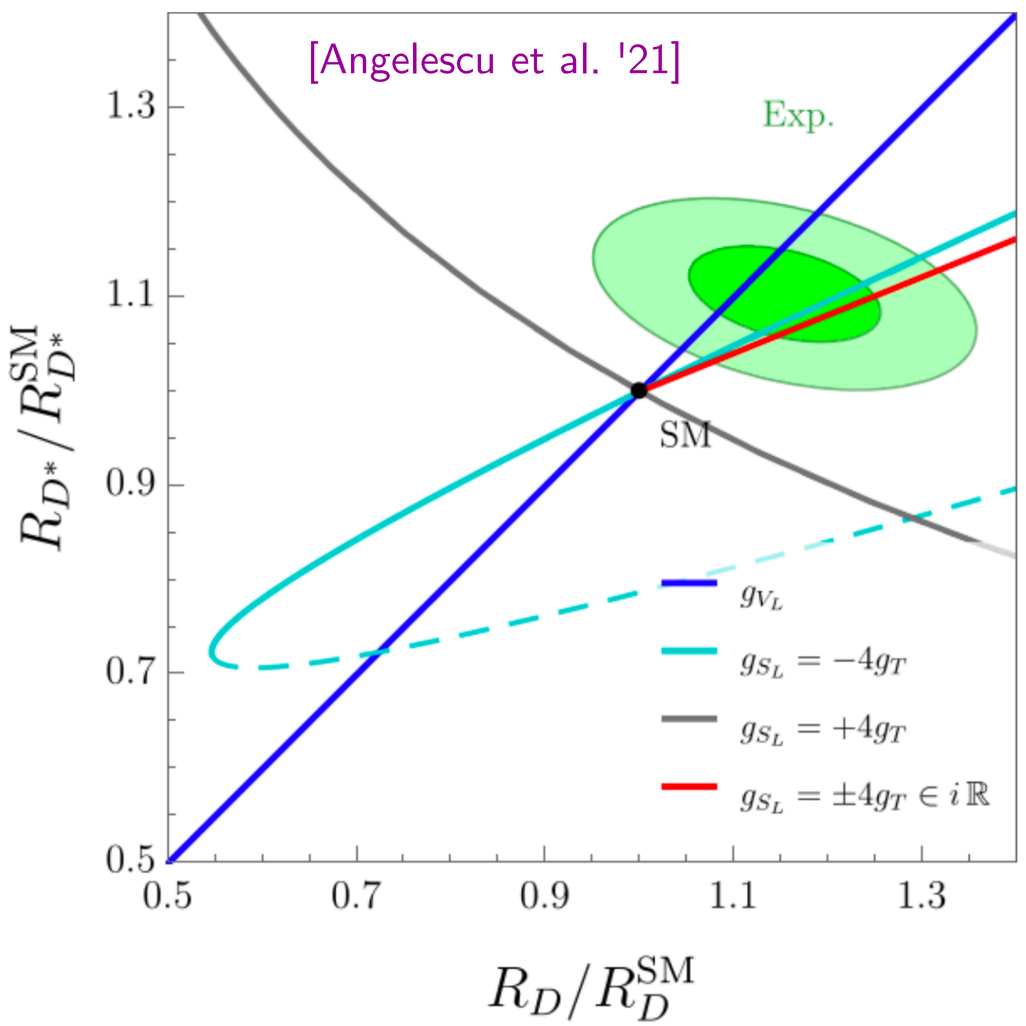

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  ii) *Other LFU ratios:*

  $$R_{D_s^{(*)}},\; R_{\eta_c},\; R_{J/\psi},\; R_{\Lambda_c},\; \dots$$

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

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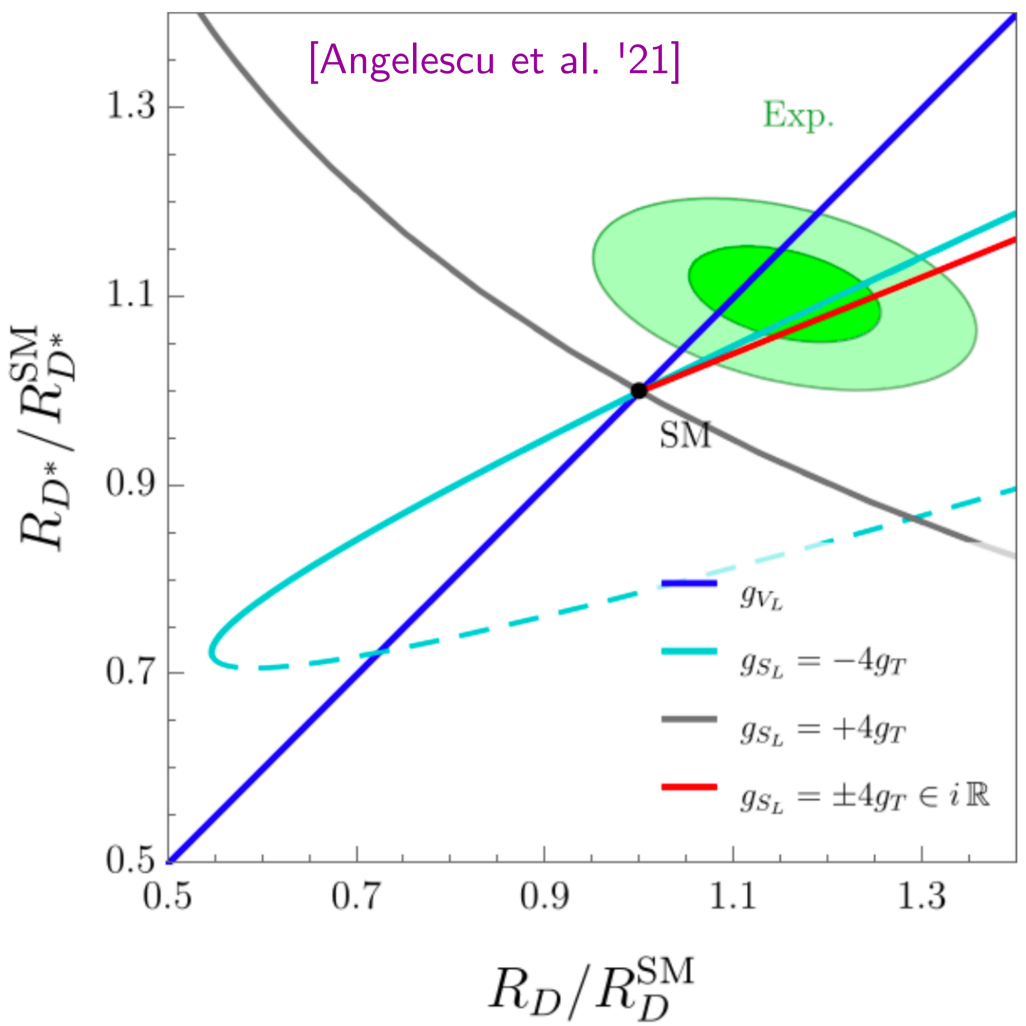

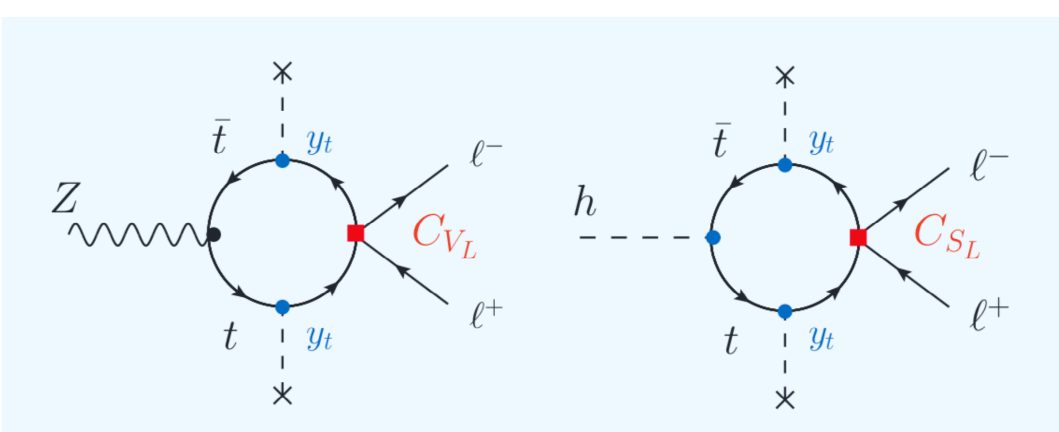

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  ii) *Other LFU ratios:*

  $$R_{D_s^{(*)}},\; R_{\eta_c},\; R_{J/\psi},\; R_{\Lambda_c},\; \dots$$

  iii) Electroweak/Higgs observables can also be a useful handle!

[Feruglio et al. '17], [Cornella et al. '18]
[Feruglio, Paradisi, **OS**. '18]

- LHCb confirmed tendency in

$$R_{J/\psi} = \frac{\mathcal{B}(B_c \to J/\psi \tau \bar{\nu})}{\mathcal{B}(B_c \to J/\psi \mu \bar{\nu})} = 0.71(17)_{\rm stat}(18)_{\rm syst}$$

[LHCb, 1711.05623]

⇒ Larger than SM prediction $R_{J/\psi}^{\rm SM} = 0.258(4)$, but with **sizeable exp. uncertainty**.

⇒ Theory input for $B_c \to J/\psi$ **form-factors** was the **dominant syst. uncertainty** in 2017. This is **no longer a limitation** thanks to recent LQCD results in [HPQCD, 2007.06957].

- **[NEW]** First measurement of $\Lambda_b \to \Lambda_c \tau \bar{\nu}$ decays:

$$R_{\Lambda_c} = \frac{\mathcal{B}(\Lambda_b \to \Lambda_c \tau \bar{\nu})}{\mathcal{B}(\Lambda_b \to \Lambda_c \mu \bar{\nu})} = 0.242(26)_{\rm stat}(40)_{\rm syst}(59)_{\rm ext}$$

[LHCb, 2201.03497]

⇒ Prediction (SM and beyond): $\dfrac{R_{\Lambda_c}}{R_{\Lambda_c}^{\rm SM}} \approx 0.26\, \dfrac{R_D}{R_D^{\rm SM}} + 0.74\, \dfrac{R_{D^*}}{R_{D^*}^{\rm SM}}$ [Blanke et al. '18]

⇒ Compatible with $R_{\Lambda_c}^{\rm SM} = 0.333(10)$ [Detmold et al., '15]; **large exp. uncertainty**.

⇒ The BR into muons is an **external input** from DELPHI **(!)**.

More exp. information is more than welcome here!

Lepton Flavor Universality

- R_K and R_{K^*}: current status
- New Physics interpretations

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

Experiment

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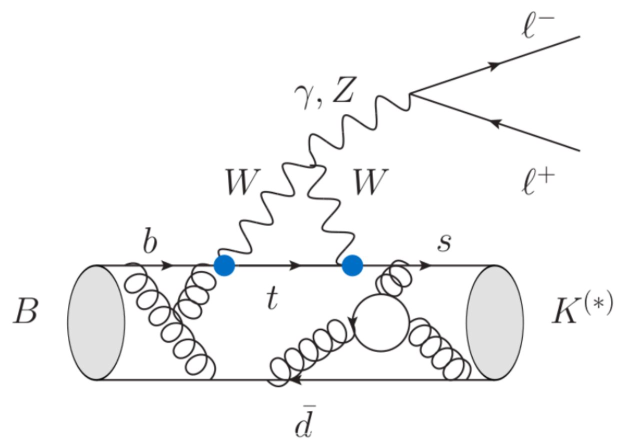
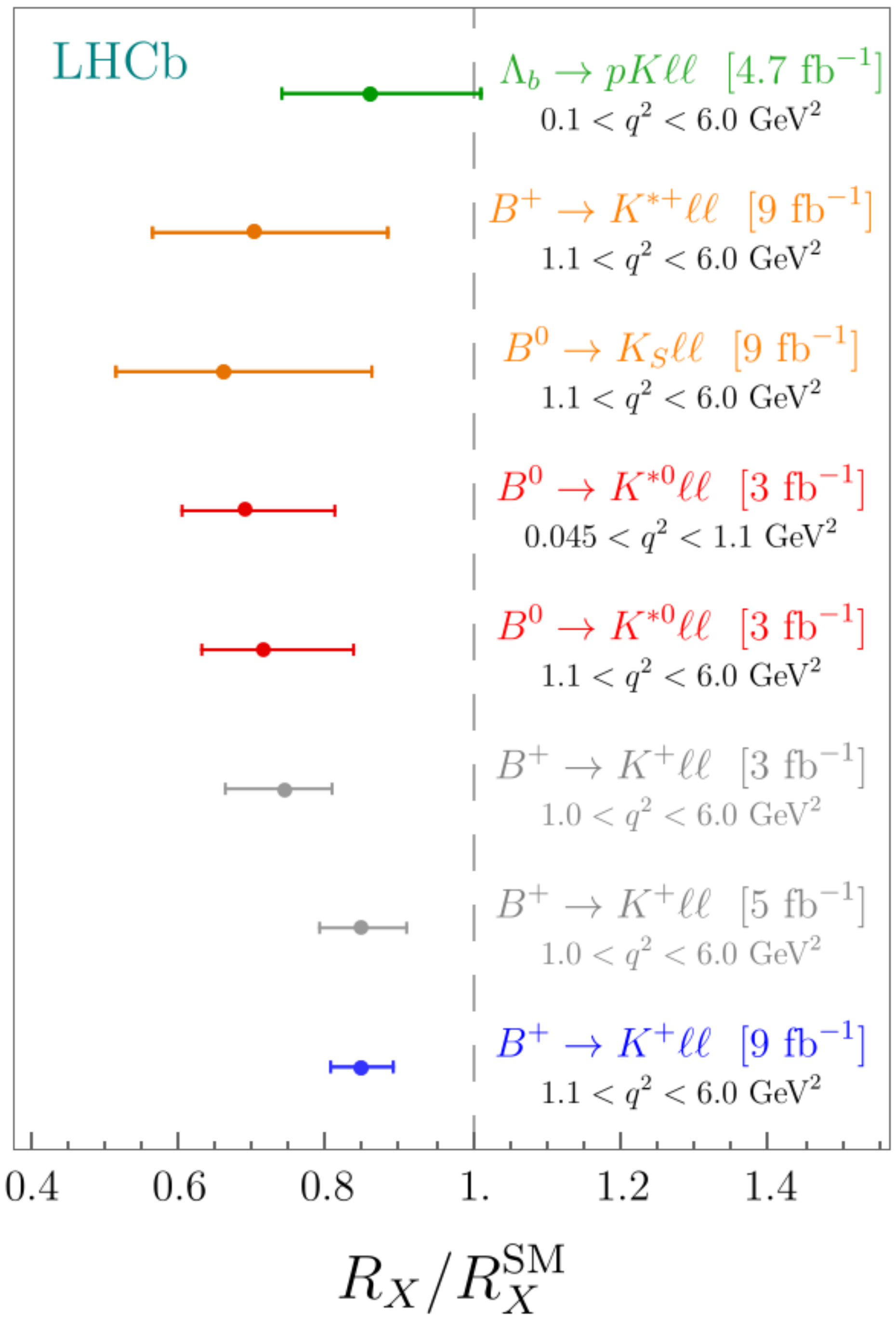




Theory (loop induced)

- 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**

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

See talk by N. Mahmoudi

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

- **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]

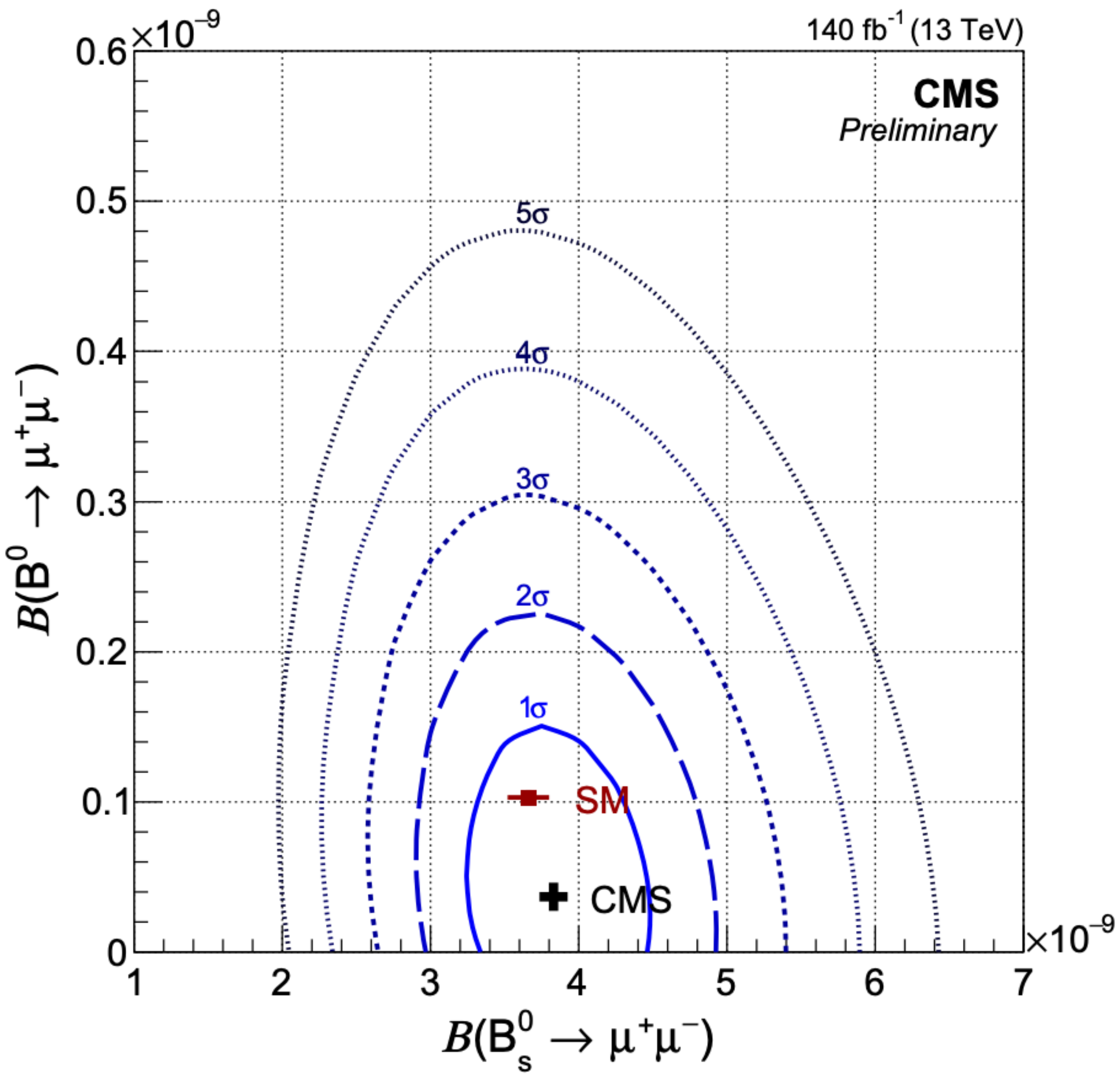
$$\overline{\mathcal{B}}(B_s \to \mu\mu)^{\text{SM}} = (3.66 \pm 0.14) \times 10^{-9}$$

[Beneke et al. '19]

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

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

[**NEW!** CMS '22]



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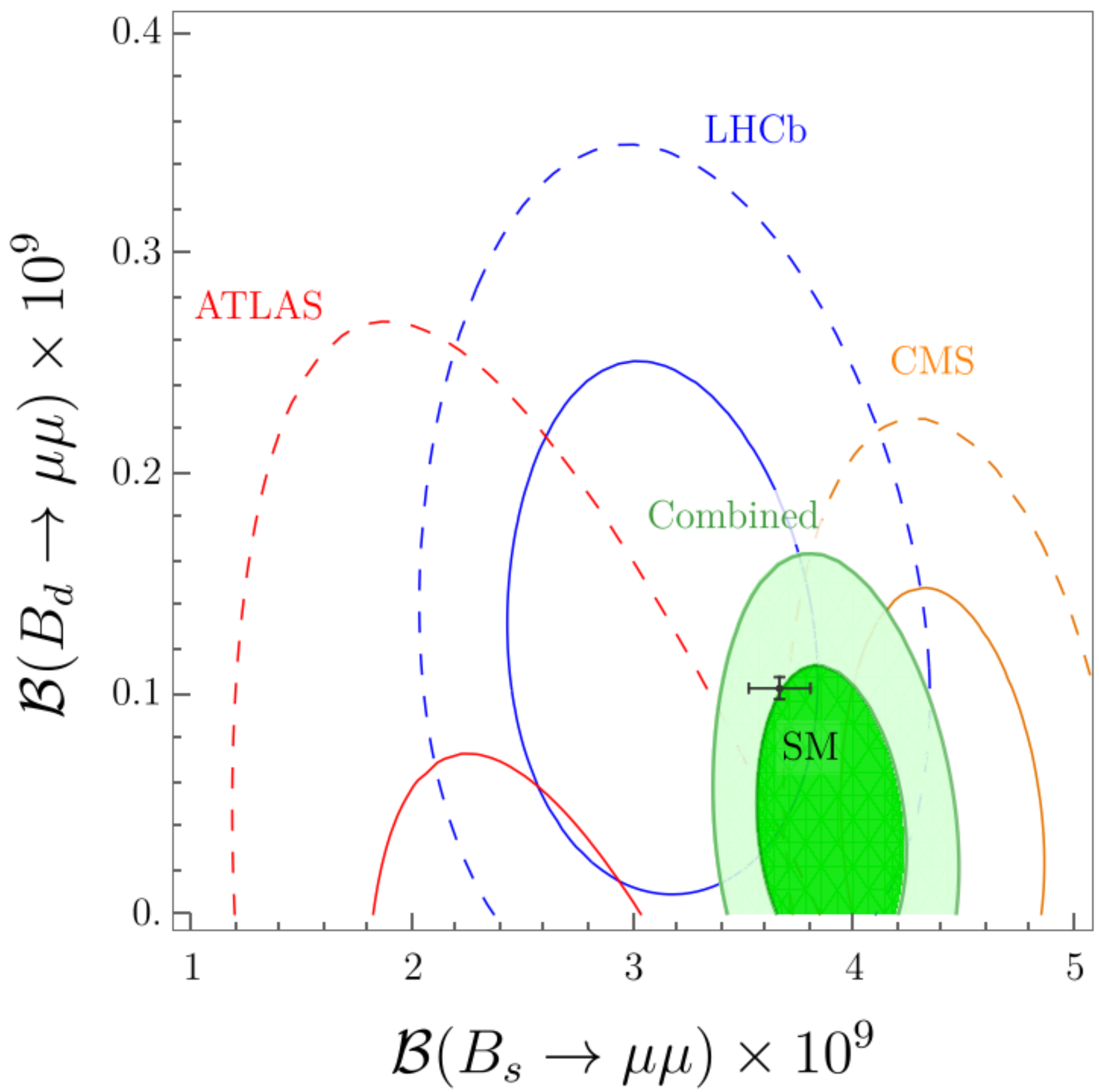
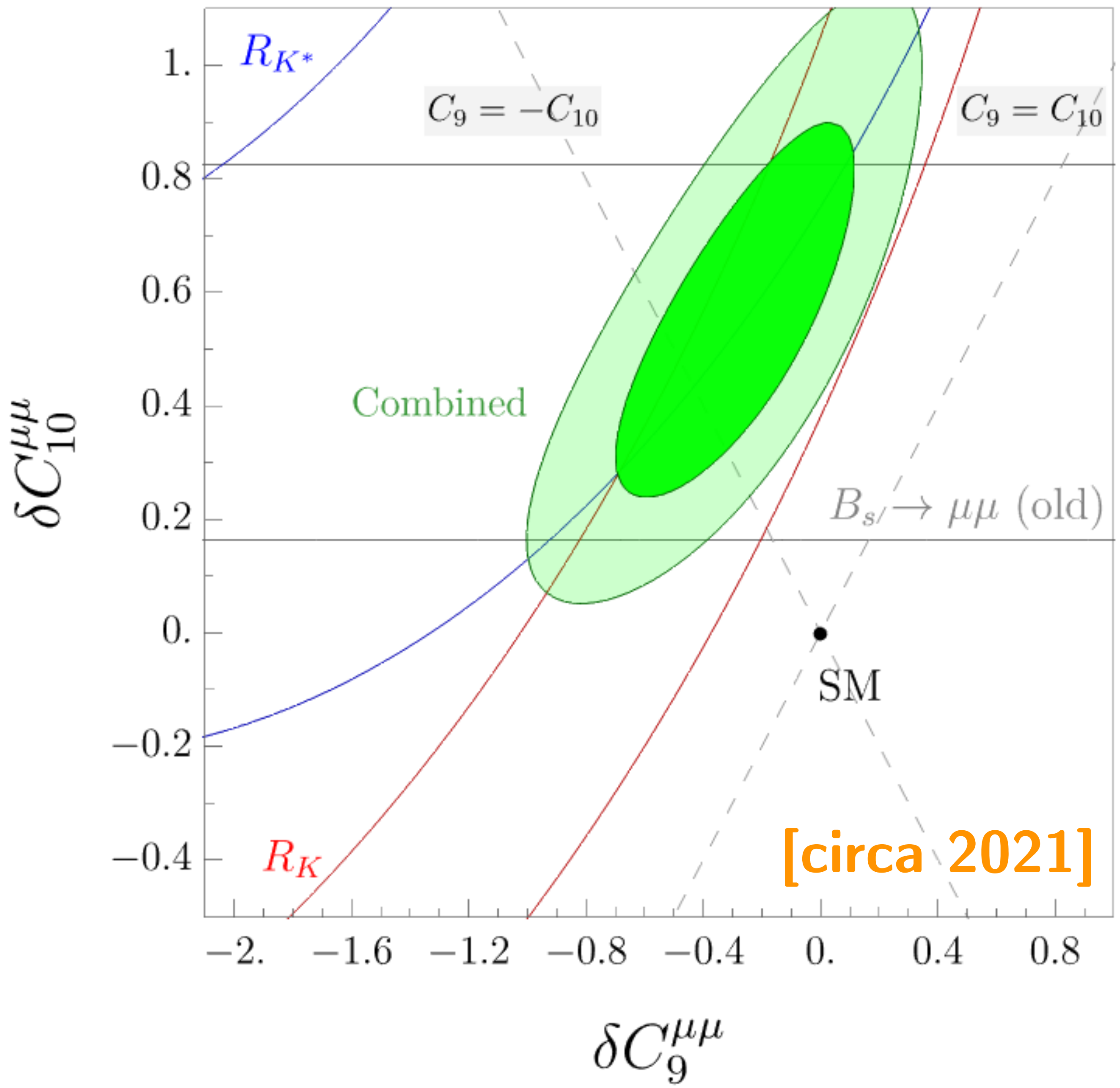


- **Good agreement** between **CMS** and **LHCb** results with the SM prediction.

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

Update of [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 LFU data.

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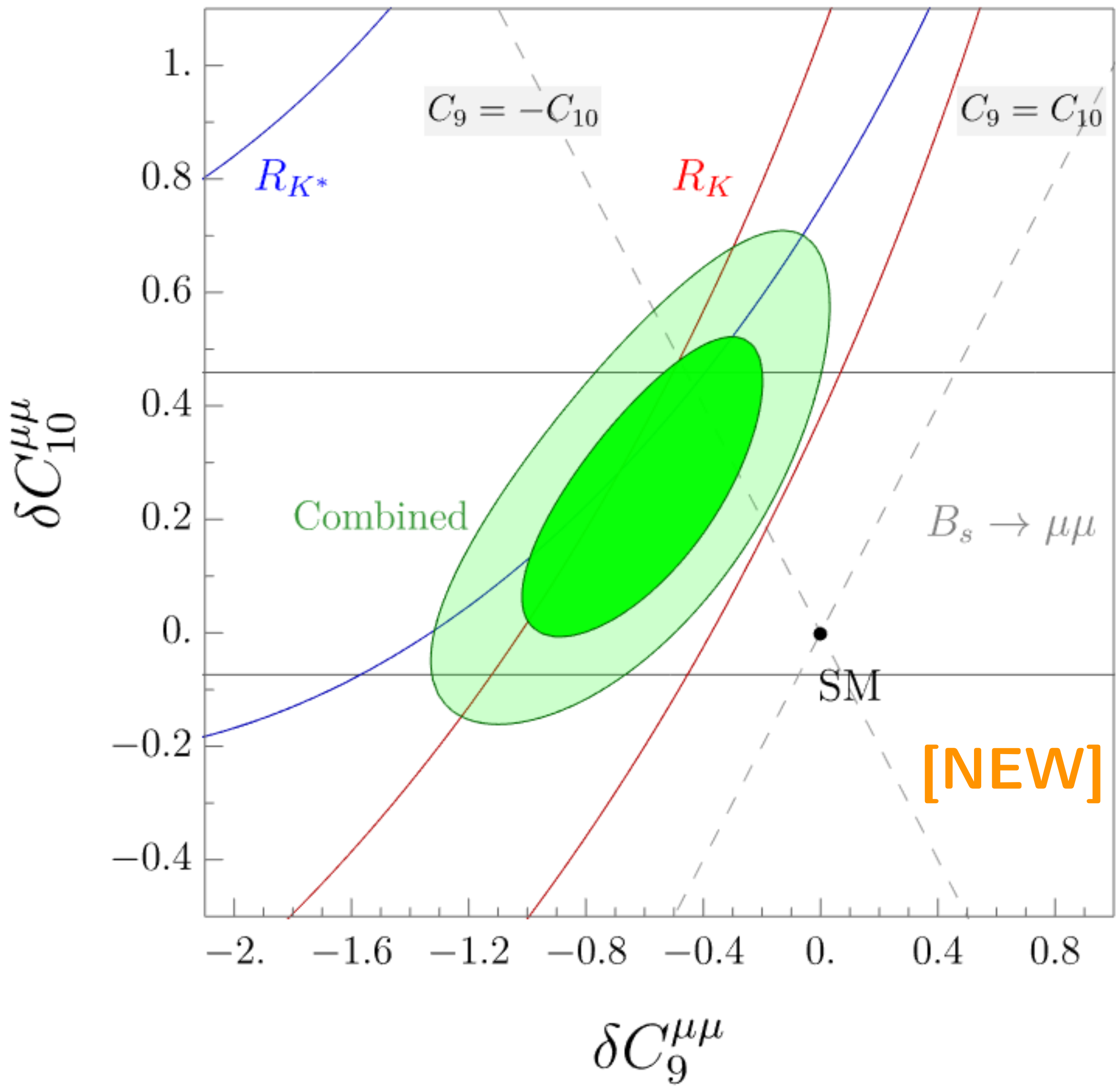

- Only vector(axial) coefficients can accommodate LFU data.
- $B_s \to \mu\mu$ slightly disfavors the pure left-handed solution: $\delta C_9^{\mu\mu} = -\,\delta C_{10}^{\mu\mu}$.

*See Nazila's talk for global $b \to s\ell\ell$ fit!

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

From EFTs to concrete models

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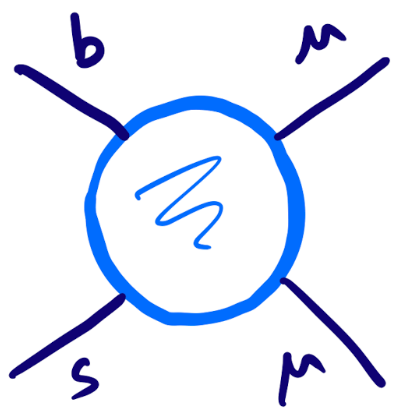
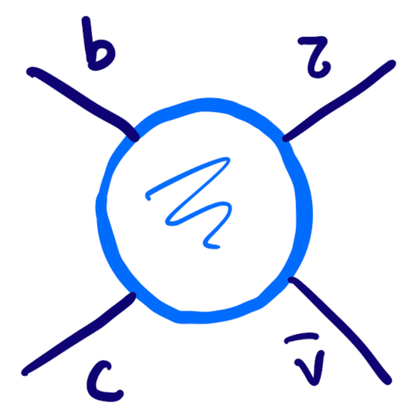
- What is the **scale of New Physics**?
  - For perturbative couplings:

[Di Luzio et al. '17]

$$\Lambda_{R_{K^{(*)}}} \lesssim 30\ \text{TeV} \qquad \Lambda_{R_{D^{(*)}}} \lesssim 3\ \text{TeV}$$





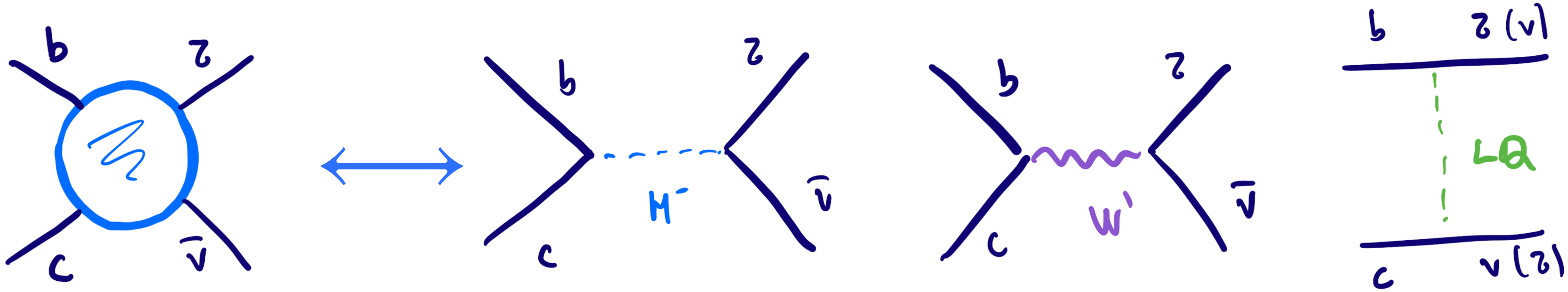
- *Good agreement* between theory and exp. in LFU tests with *K*-, *D*-meson and τ-lepton decays.

$\Rightarrow$ **New Physics couplings** to SM fermions needs to be **hierarchical** (hint of a flavor symmetry?).

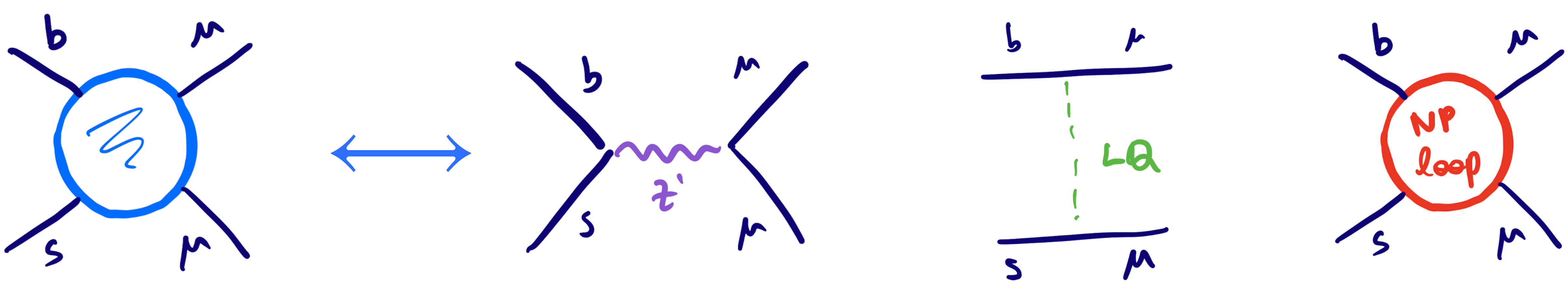
From EFTs to concrete models

Many papers in the literature...

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



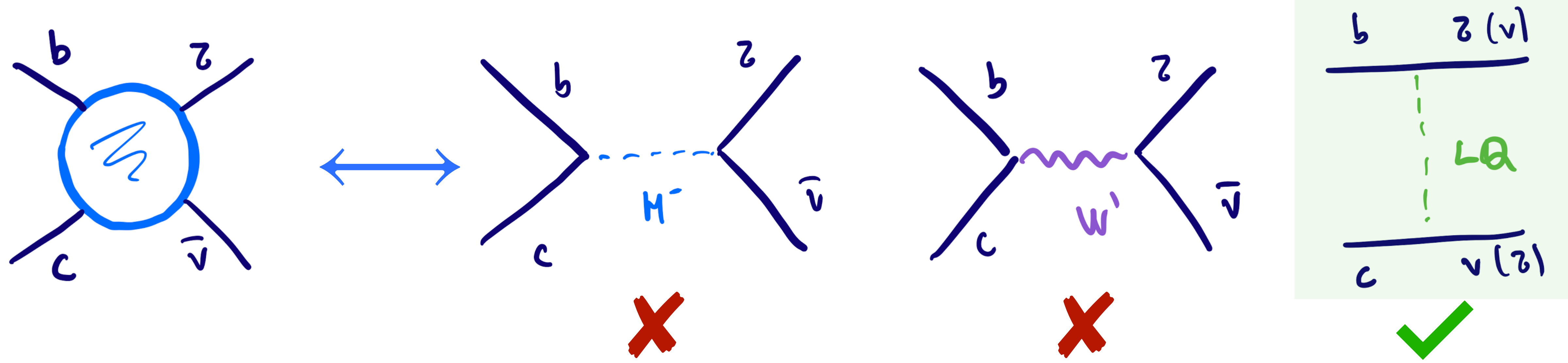
- $b \to s\ell\ell$:



From EFTs to concrete models

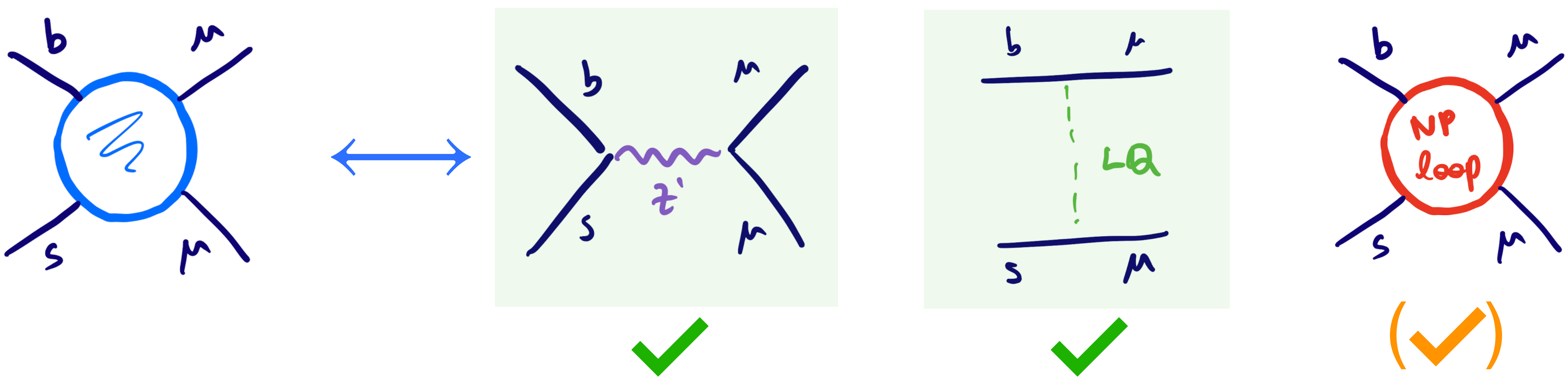
Many papers in the literature...

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



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

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



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

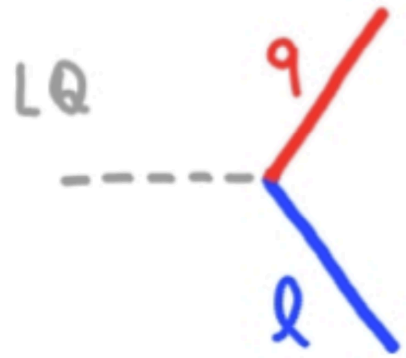
Which leptoquark?

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

[Buchmuller, Wyler. '88]

Few scenarios are viable!

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



	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 $(\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗	✗

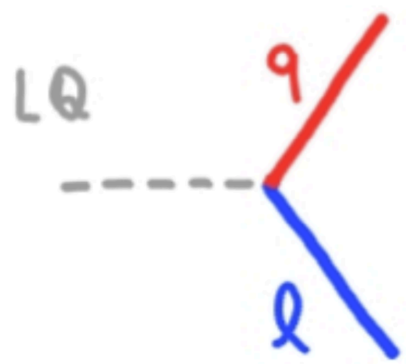
Which leptoquark?

[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.
  - $\mathcal{G}_{\mathrm{PS}} = SU(4) \times SU(2)_L \times SU(2)_R$ contains $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$
  - 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]

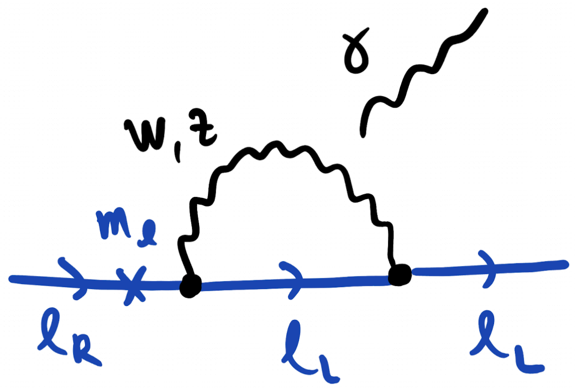
Muon g-2: another LFU hint?*

See talks by G. Colangelo, T. Blum, M. Knecht

*Considering the TH initiative prediction. Disagreement between LQCD [BMW '21] and dispersive determinations of HVP still to be clarified!

EFT for Δa_μ

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

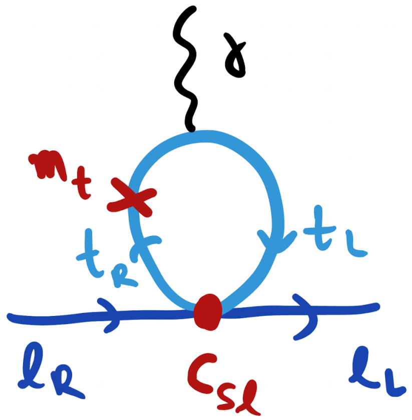


$$\mathcal{L}_{\text{eff}} \supset \frac{y_\ell}{16\pi^2}\frac{C_D^{ij}}{\Lambda^2}\bar{L}_i H \sigma^{\mu\nu} e_{Rj} F_{\mu\nu} + \text{h.c.}$$

[Many papers...]

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

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



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

e.g.,

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

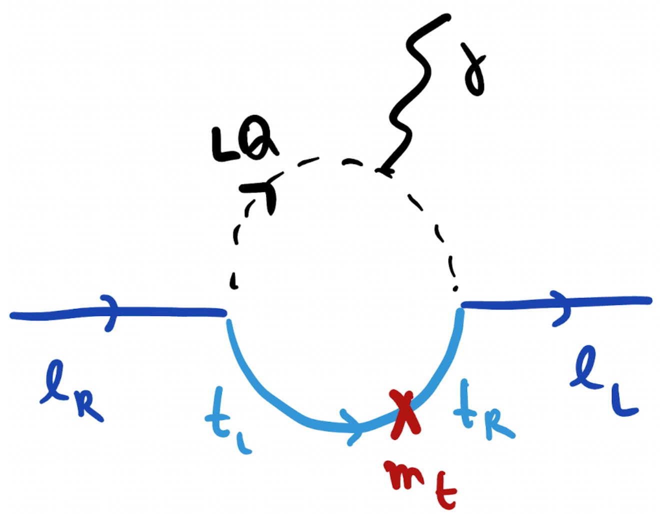
[Feruglio, Paradisi, **OS**, '18] [Buttazzo et al. '20][Fajfer et al. '21], [Aebischer et al., '21], [Crivellin et al. '21]

These contributions can be generated by LQs, **but... which one**?

Scalar LQs for Δa_μ ?

- LQs should couple to $\mu_L\, t_R$ and $\mu_R\, t_L$:

[Cheung et al., '01], [Crivellin et al. '21], [Dorsner, Fajfer, **OS**. '19]



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

$\Rightarrow$ Two viable candidates (R_2 and S_1), but not the ones needed for $b \to s\mu\mu$.

$\Rightarrow$ Connection to $b \to c\tau\bar{\nu}$ is difficult because of LFV bounds (*e.g.*, $\tau \to \mu\gamma$). *Peculiar structure* of the Yukawas and/or *fine-tuning* is needed.

See e.g. [Gherardi et al. '20]

Difficult to reconcile LFU and **muon g-2** puzzles within minimalistic models. Possible in *next-to-minimal* scenarios...

Predictions at low- and high-energies

B-decays with missing energy

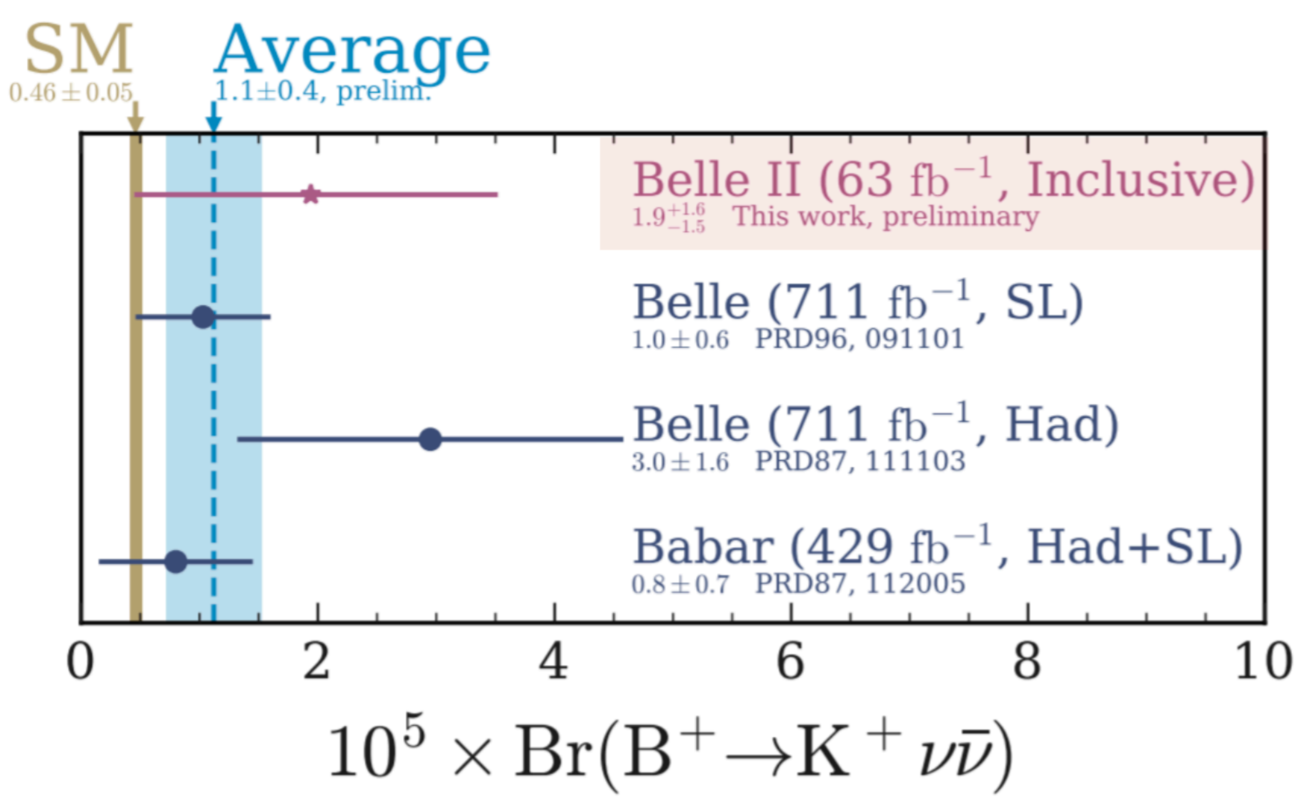
- **Clean observable** in the SM:

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) = 5.7(4) \times 10^{-6}$$

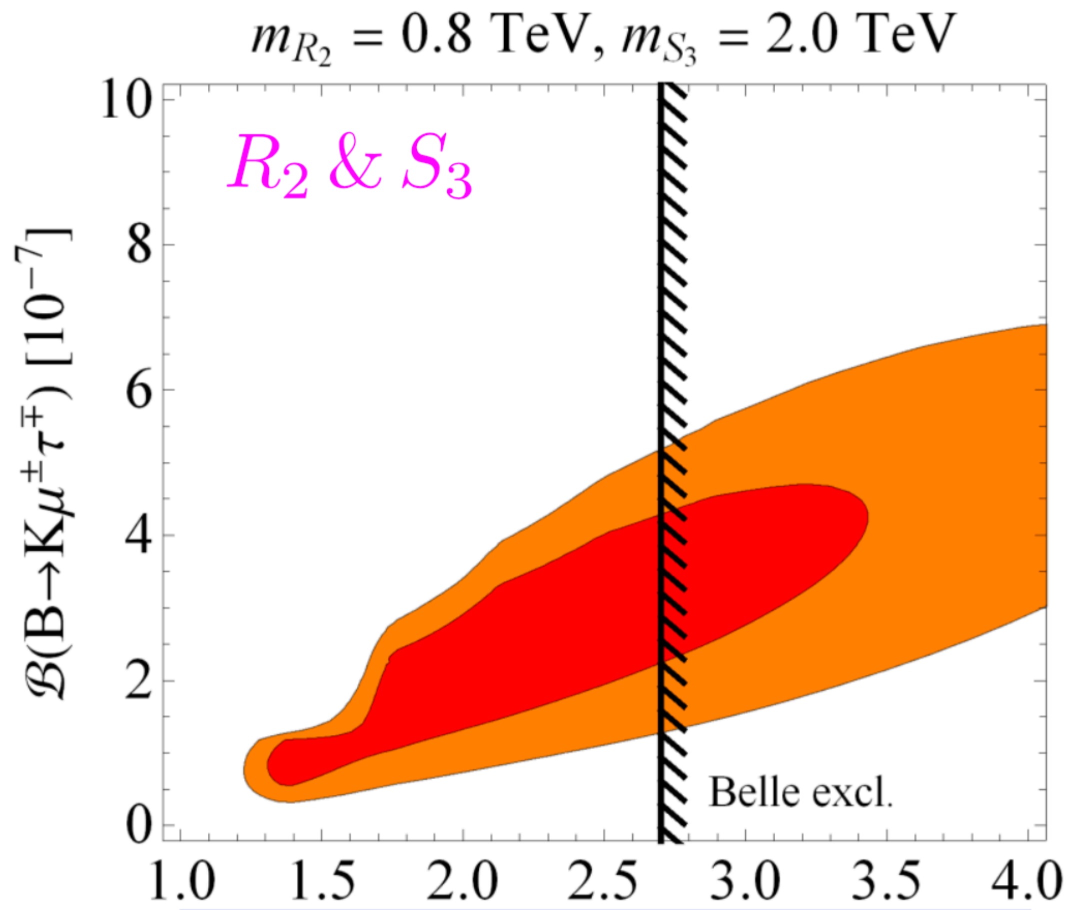
[Buras et al. '14], [HPQCD. '22]

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

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



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



$$R_{\nu\nu}^{(*)} = \mathcal{B}(B \to K^{(*)}\nu\nu)/\mathcal{B}(B \to K^{(*)}\nu\nu)^{SM}$$

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

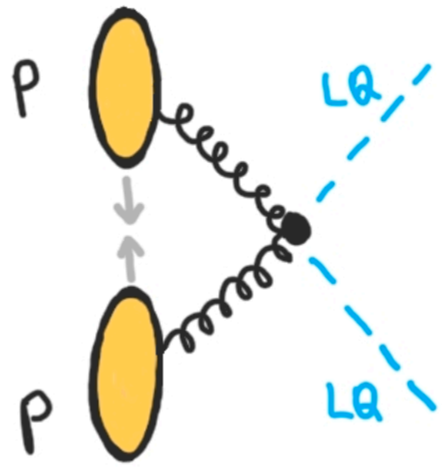
LHC constraints

See talk by Iguro

i. LQ pair-production

Production dominated by QCD:

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



$+ \cdots$

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

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

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]

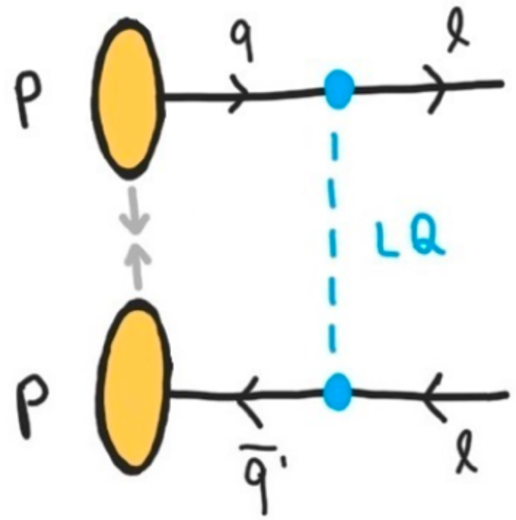
[Angelescu, Becirevic, Faroughy, Jaffredo, **OS**. '21]

LHC constraints

See talk by Iguro

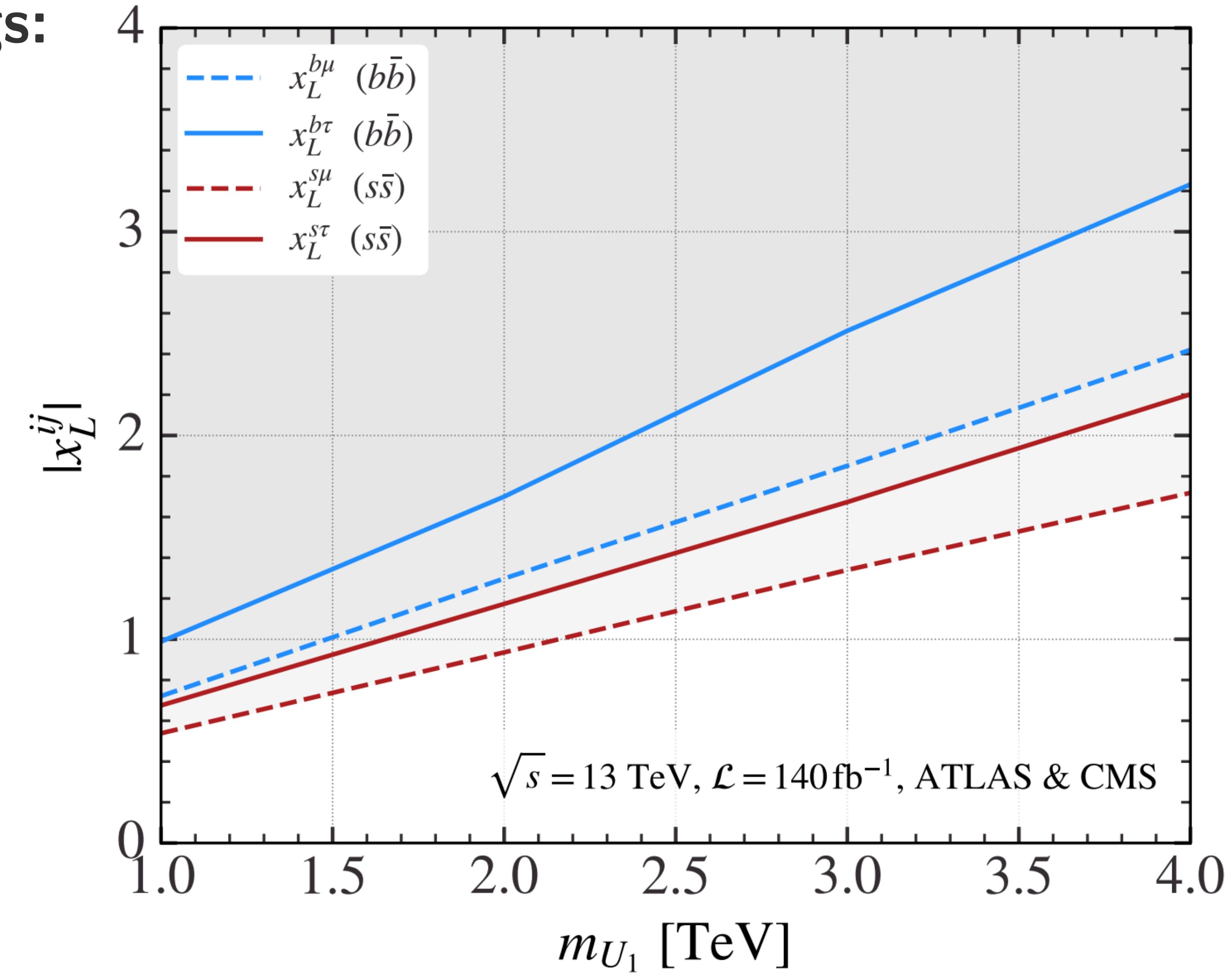
ii. Di-lepton production at high-p_T

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]

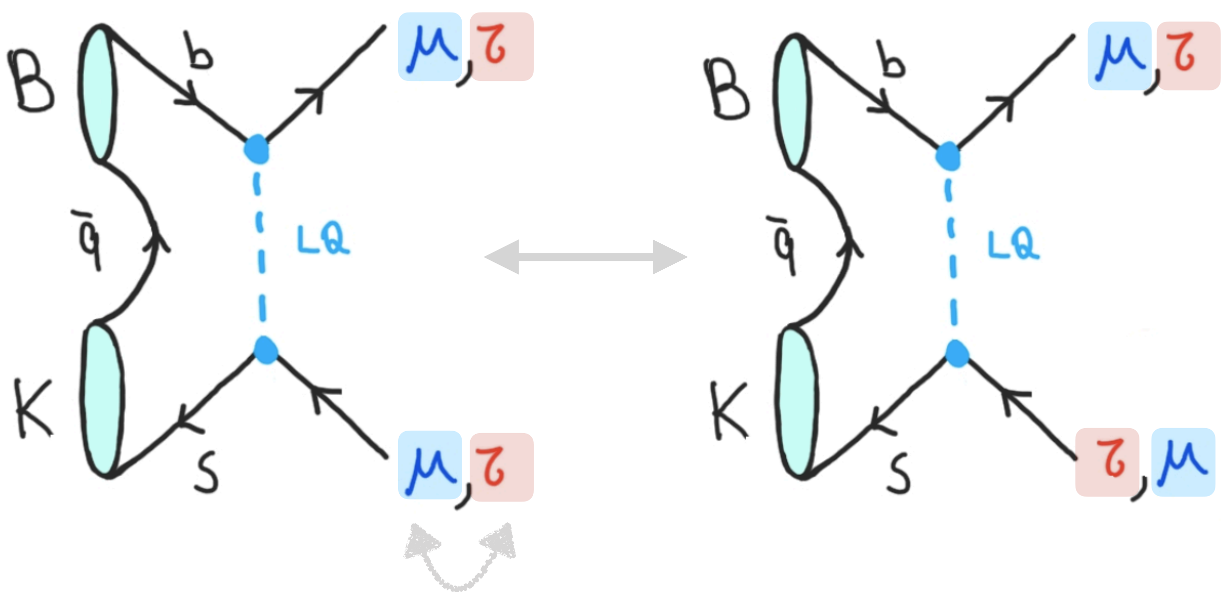
See also [Faroughy et al. '15] and following works

Lepton **F**lavor **V**iolation

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

see also [Glashow et al. '14]

- **LFU**V ↔ **LFV**:



Predictions for

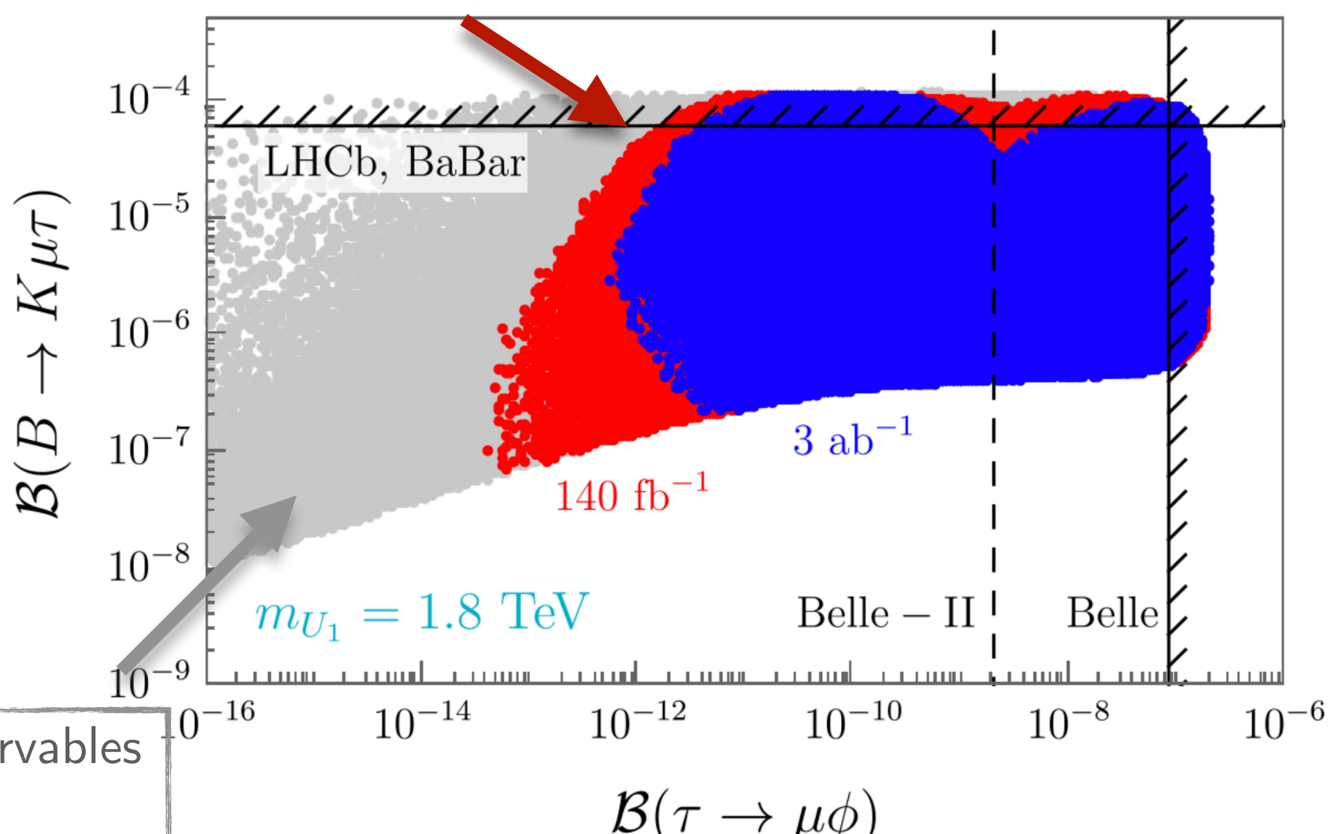
$$B_s \to \mu\tau \qquad B \to K^{(*)}\mu\tau$$

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 $\mathscr{B}(B \to K\mu\tau)$!

Several flavor observables (at tree-level)

Perspectives

Summary and perspectives

- Experimental situation of LFU violation in B-decays remains unclear.

  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.

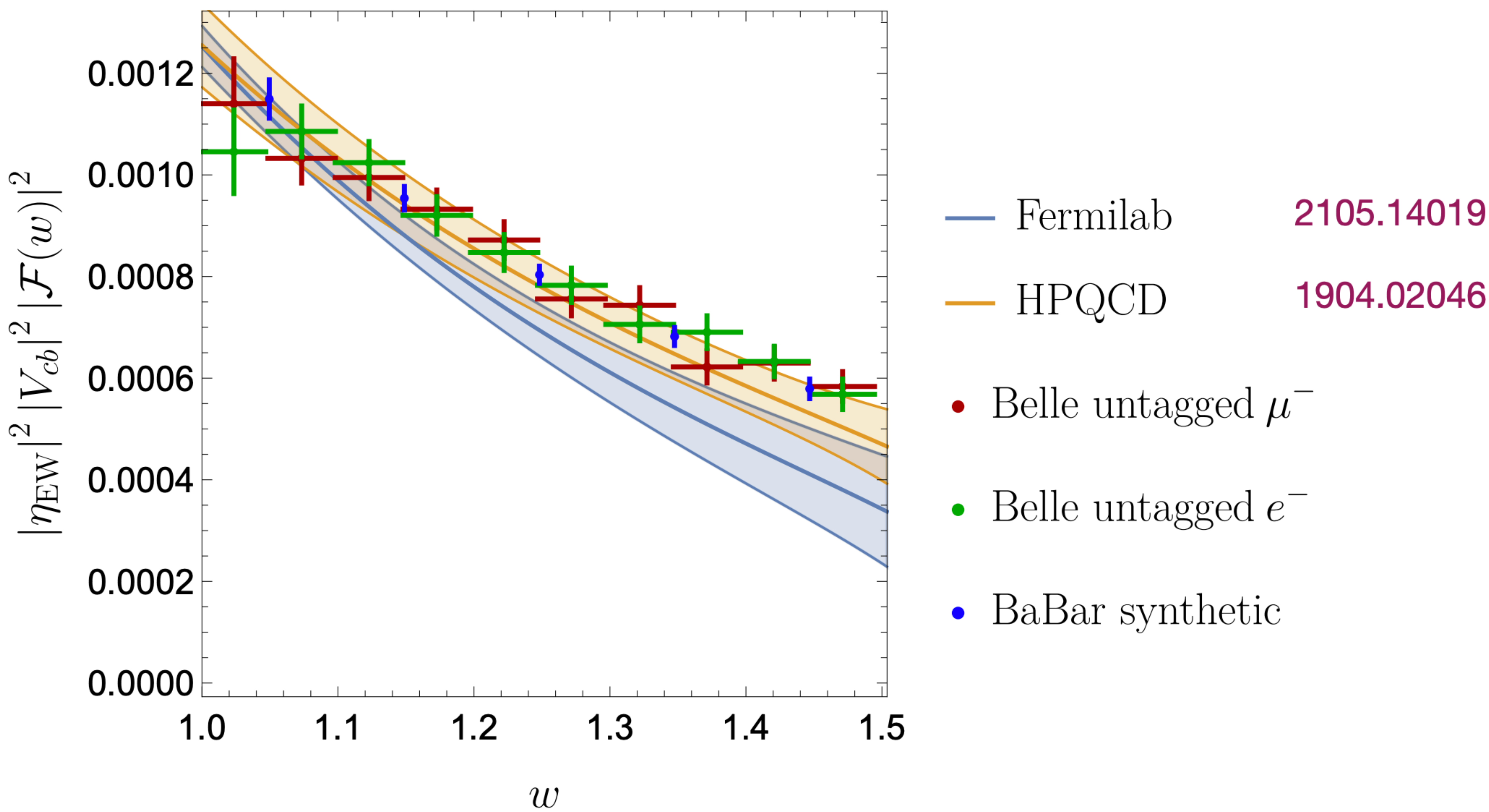
  $R_{D^{(*)}, D_s^{(*)}, \Lambda_c^{(*)},\dots}$ $\quad R_{K^{(*)}, \phi,\dots}$ $\quad B \to K^{(*)}\mu\tau$ $\quad B \to K^{(*)}\nu\bar{\nu}$ $\quad \cdots$

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

Data-driven model building!

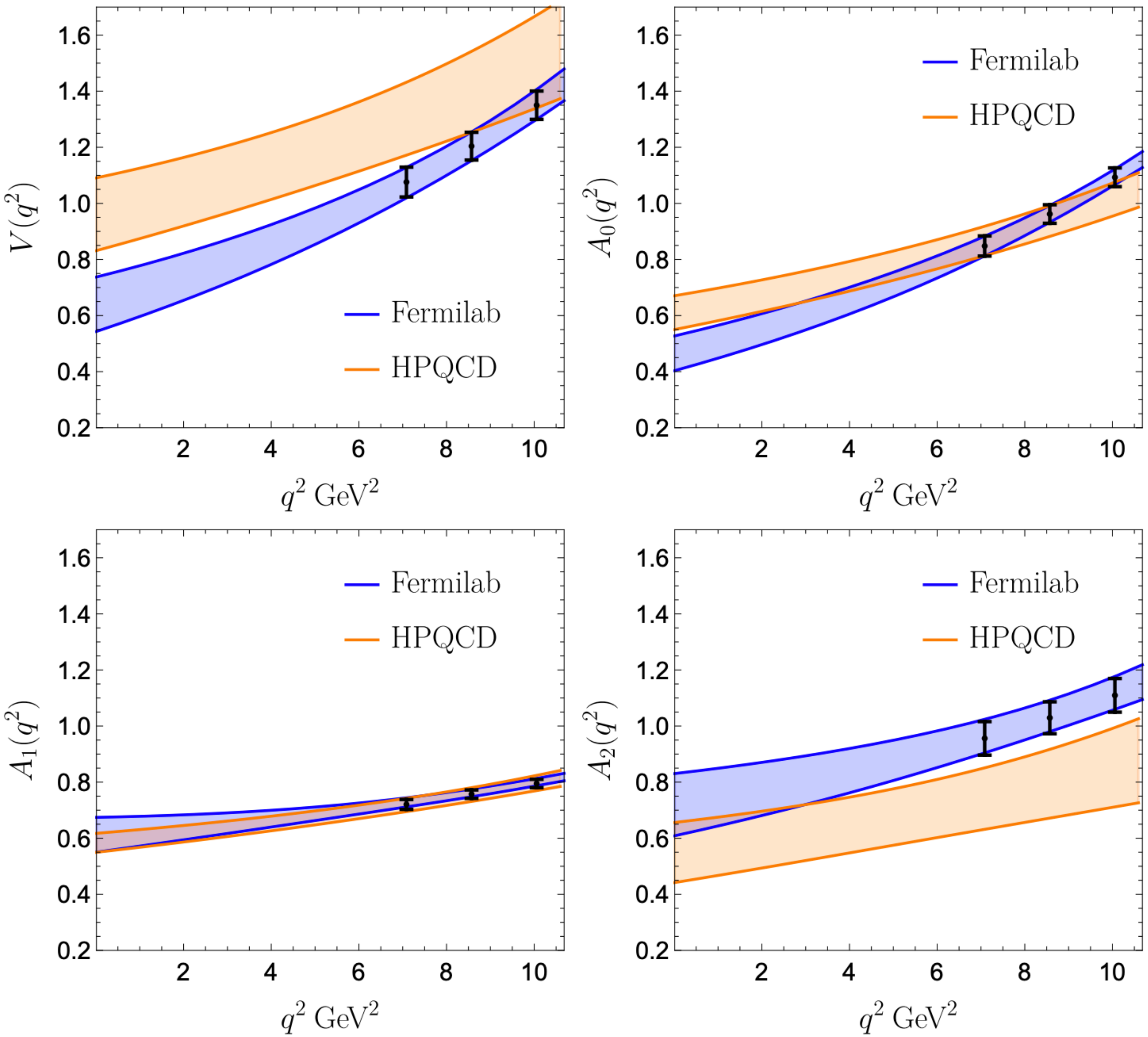
Thank you!

Back-up



- Assuming with HPQCD that $\mathcal{F}(w)^{B_s\to D_s^*} = \mathcal{F}(w)^{B\to D^*}$

$B \to D^* \ell \bar{\nu}$



1904.02046
2105.14019

[Allwicher, Faroughy, Jaffredo, **OS**, Wilsch. '22]

```
<<HighPT`
```

HighPT : High-p_T Tails

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

References: arXiv:2207.10756, arXiv:2207.10714

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

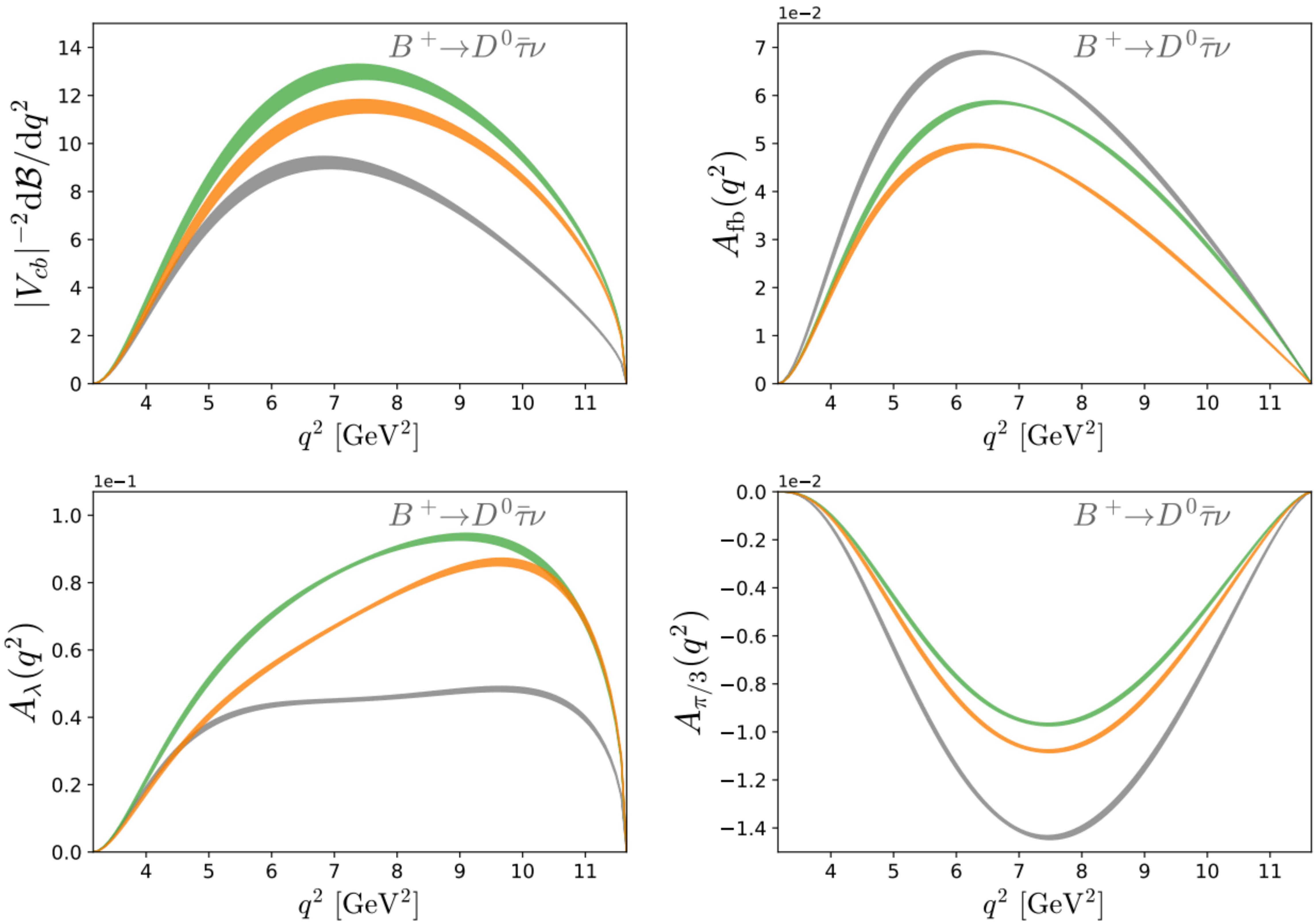
HighPT is free software released under the terms of the MIT License.

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]
$pp \to e\mu,\ e\tau,\ \mu\tau$	[arXiv:2205.06709]

*more to be included (see GitHub page)

$$\frac{\mathrm{d}\mathcal{B}^{\pm}(q^2)}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell} = a^{\pm}(q^2) + b^{\pm}(q^2)\,\cos\theta_\ell + c^{\pm}(q^2)\,\cos^2\theta_\ell\,,$$



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

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

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

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

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

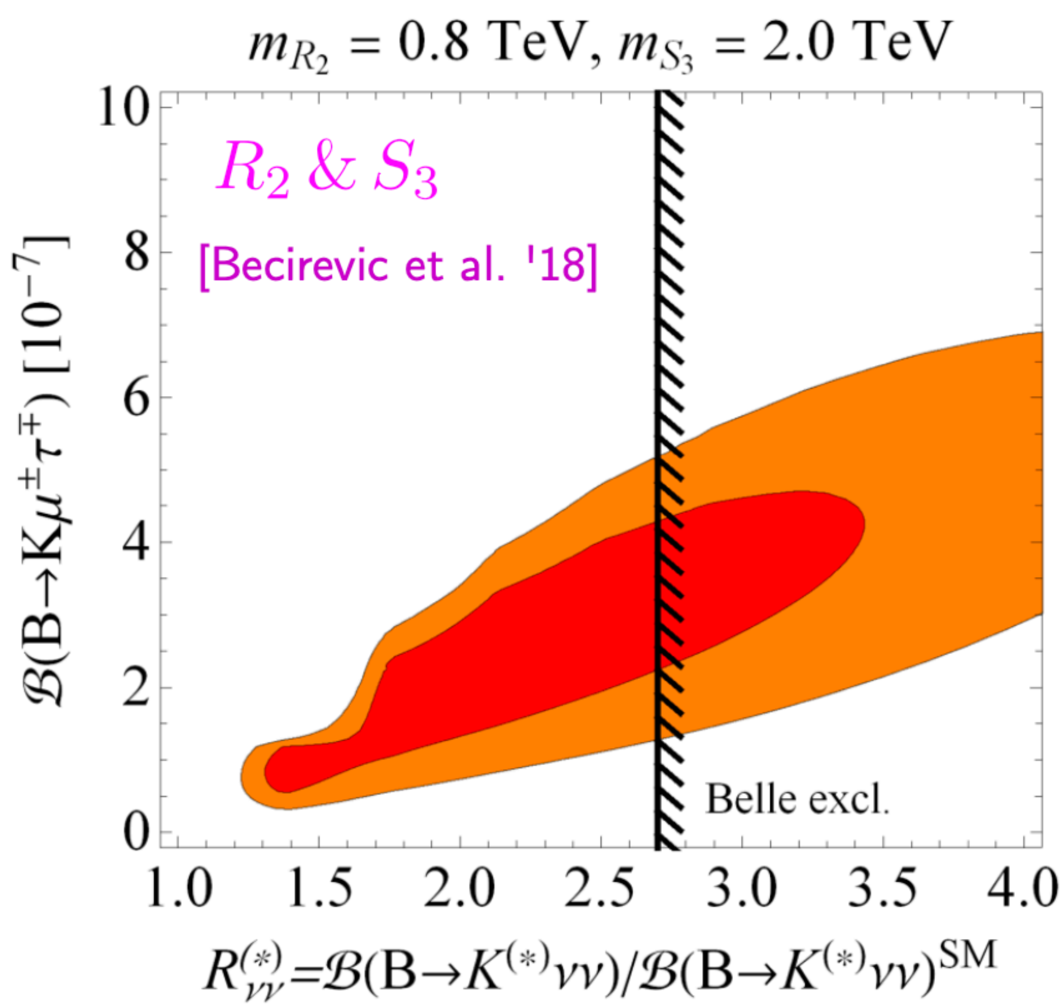
- $b \to s\mu\mu$:

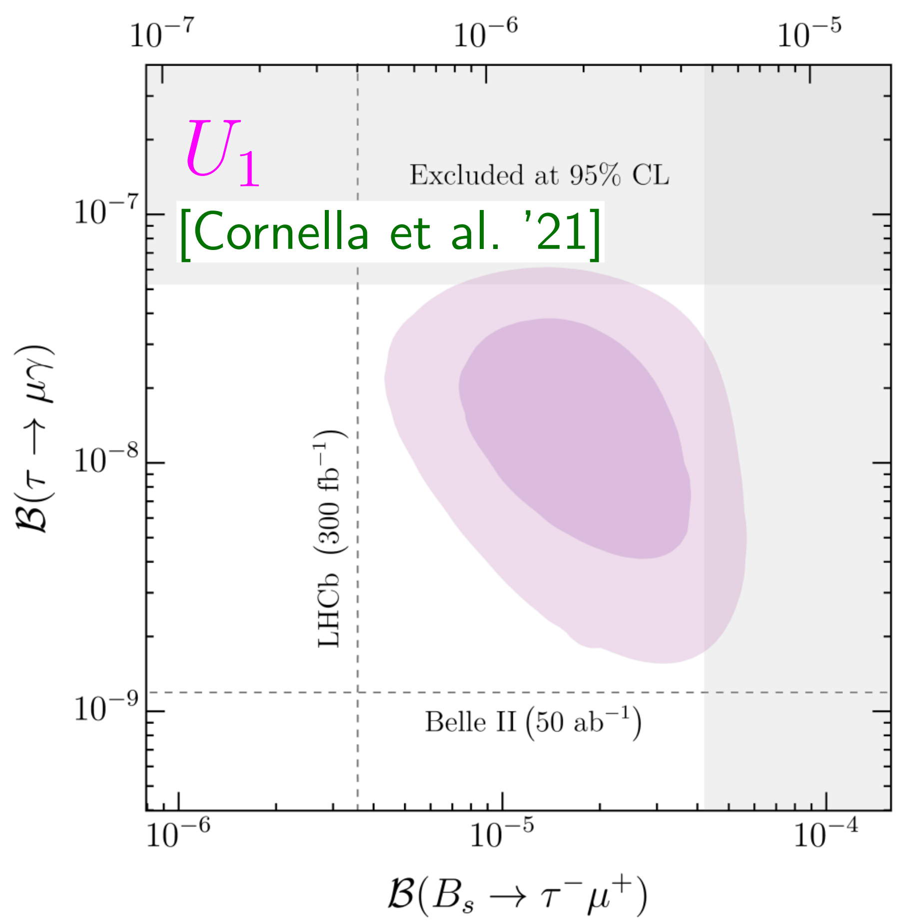
$$\mathcal{L}_{\text{eff}} \supset -\frac{\left(x_L\right)^{s\mu} \left(x_L^{b\mu}\right)^*}{m_{U_1}^2} (\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L)$$

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

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

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:

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