Flavor physics at high-p_T

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IJCLab (Orsay)

Atelier "Physique théorique des deux infinis", 07/06/21

Motivation

See talks by N. Mahmoudi, A. Gérardin and M. Frigerio

- **Flavor physics** observables **can probe** physics at very **high-energy scales.** **Combined effort** of **exp.** and **theory** (LQCD) to constantly **improve precision**.

e.g.,

$$\Delta F = 2 \qquad \mathcal{L} \supset \frac{1}{\Lambda^2}(\bar{s}_L \gamma^\mu d_L)(\bar{s}_L \gamma_\mu d_L) \quad \Rightarrow \quad \Lambda \gtrsim 10^3 \text{ TeV}$$

- *However*, **flavor is not always** the **best probe** of a given 4-fermion operator; its **sensitivity depends** on the **flavor structure** of **New Physics (NP)** couplings – which is still uknown:

$\Rightarrow$ e.g., *flavor-conserving* operators are *poorly constrained* at low-energies; LHC probes can be very useful in this case!

- It is **fundamental** to **combine** all **possible approaches** *(flavor and LHC)!*

$\Rightarrow$ Main tools are Effective Field Theories (*as long as they are valid*) and concrete NP models.

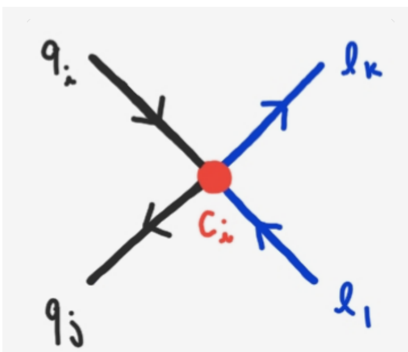
This talk: Explore the **complementarity** of **low** and **high-energy probes**.

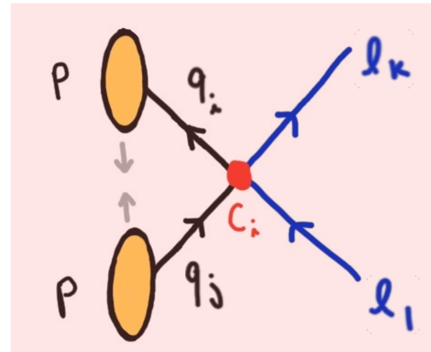
How to probe flavor at high-p_T?

Low vs. high-p_T constraints

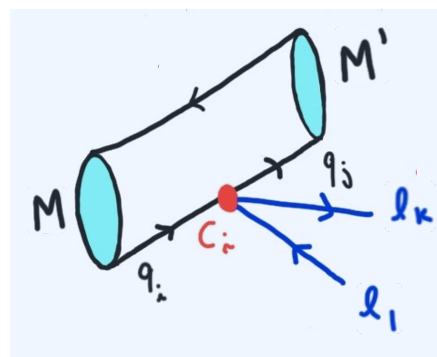
Flavorful New Physics?

Effective operator





$$pp \to \ell_k \ell_l$$

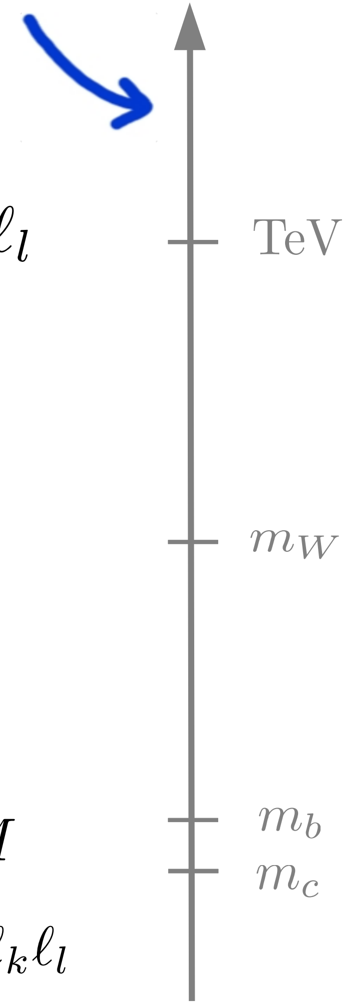


$$M \to \ell_k \ell_l$$

$$\ell_k \to \ell_l M$$

$$M \to M' \ell_k \ell_l$$

$$\dots$$



High-p_T searches (CMS and ATLAS) **can probe** the **same operators** constrained by **flavor-physics experiments** (NA62, KOTO, BES-III, LHCb, Belle-II...).

see [Faroughy et al. '16], [Greljo et al. '17, '18], [Fuentes-Martin et al., '20], [Angelescu et al. '20]...

i) LHC is a flavorful experiment

LHC collides **five quark-flavors:**

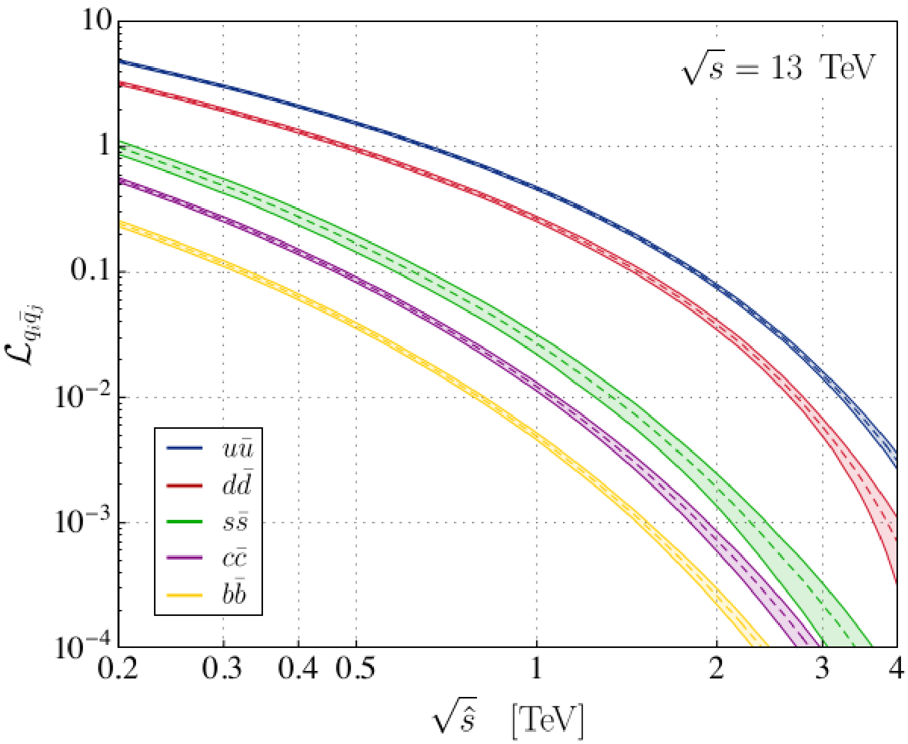
Partonic cross-section

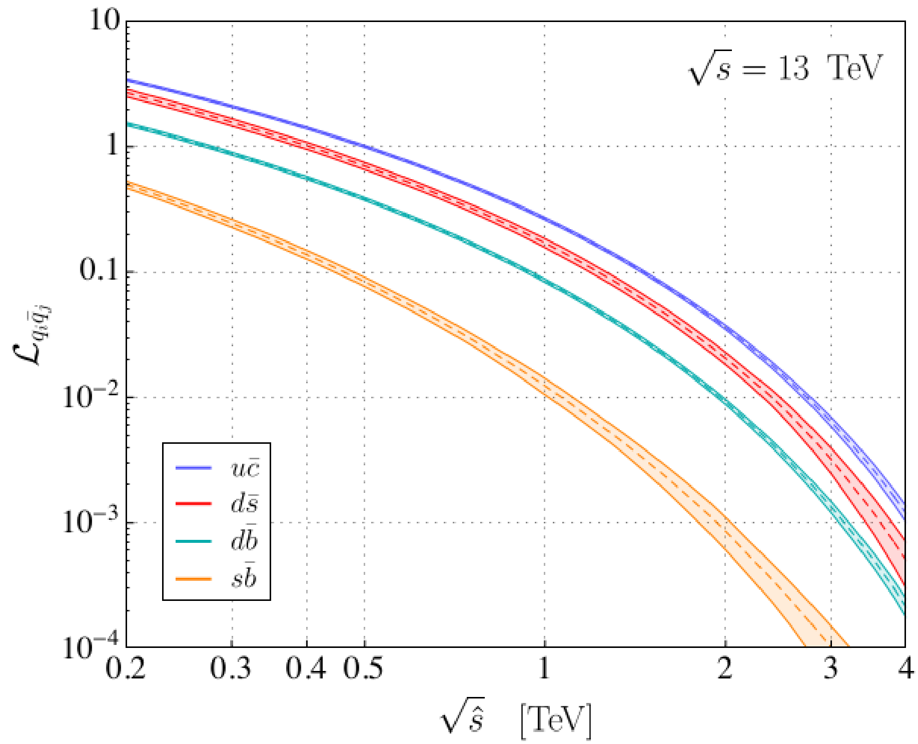
$$\sigma(pp \to \ell\ell') = \sum_{ij} \int \frac{d\tau}{\tau} \mathcal{L}_{q_i\bar{q}_j}(\tau)\, \hat{\sigma}(q_i\bar{q}_j \to \ell\ell')_{\hat{s}=s\tau}$$

$$\tau = \hat{s}/s$$
$$\hat{s} = m^2_{\ell\ell'}$$
$$\sqrt{s} = 13 \text{ TeV}$$

$i = j$ $\qquad$ $i \neq j$

Parton luminosities:





[PDF4LHC15_nnlo_mc]

ii) Energy helps precision

see e.g. [Farina et al., 16']

Dimension-6 operators:

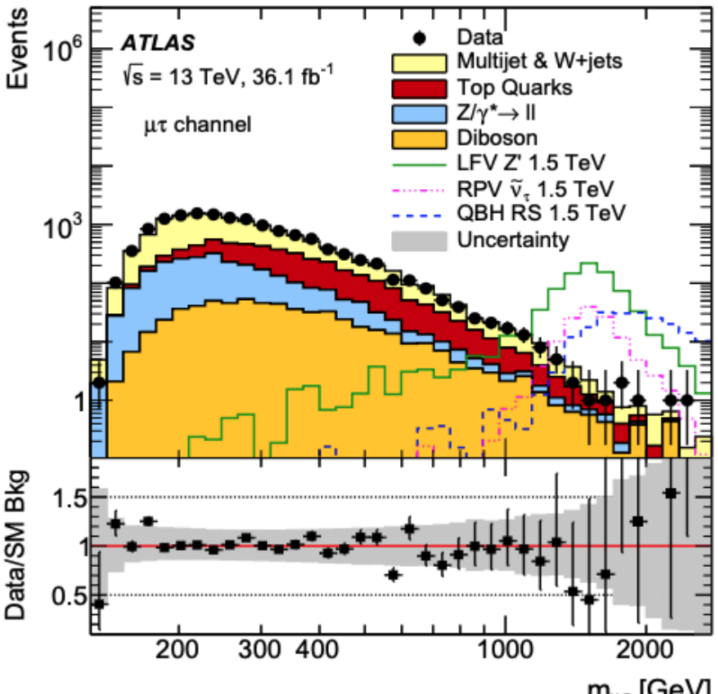
$$\mathcal{L}_{\text{eff}} \supset \frac{C_{\text{eff}}}{\Lambda^2}\,\mathcal{O}^{(6)} \qquad \Longrightarrow \qquad \hat{\sigma} \propto \frac{\hat{s}}{\Lambda^4}|C_{\text{eff}}|^2 + \ldots$$

Energy-growth can partially overcome heavy-flavor PDF suppression.

$pp \to \mu\tau$

Strategy:

Recast LFV **di-lepton searches** and look for **NP effects** in the **tails** of the **invariant mass-distribution** (where S/B is large).



[ATLAS. 1807.06573]

Caveat: EFT must be valid $(\sqrt{s} \ll \Lambda)$; Otherwise, use explicit UV model.

Concrete examples:

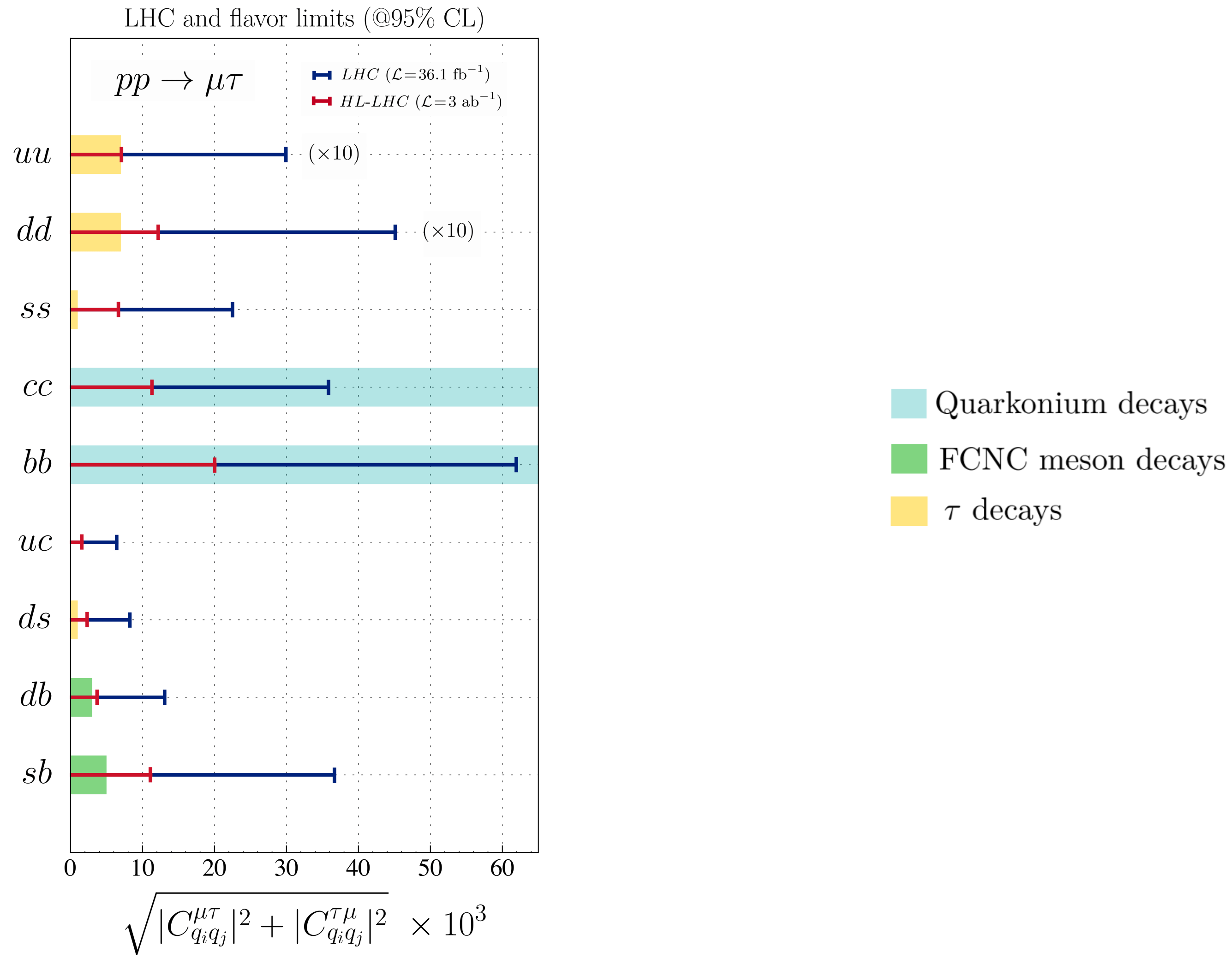
- **L**epton **F**lavor **V**iolation in meson decays
- Leptoquarks and **L**epton **F**lavor **U**niversality

Example: Lepton Flavor Violation (LFV)

e.g.,

$$\mathcal{L}_{\rm eff} = \sum \frac{C_{q_i q_j}^{\ell_k \ell_l}}{v^2} \left(\bar{q}_{Li}\gamma^\mu q_{Lj}\right)\left(\bar{\ell}_{Lk}\gamma_\mu \ell_{Ll}\right)$$

[SMEFT: $\mathcal{O}_{lq}^{(1)}$, $\mathcal{O}_{lq}^{(3)}$]



*See back-up for other channels.

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

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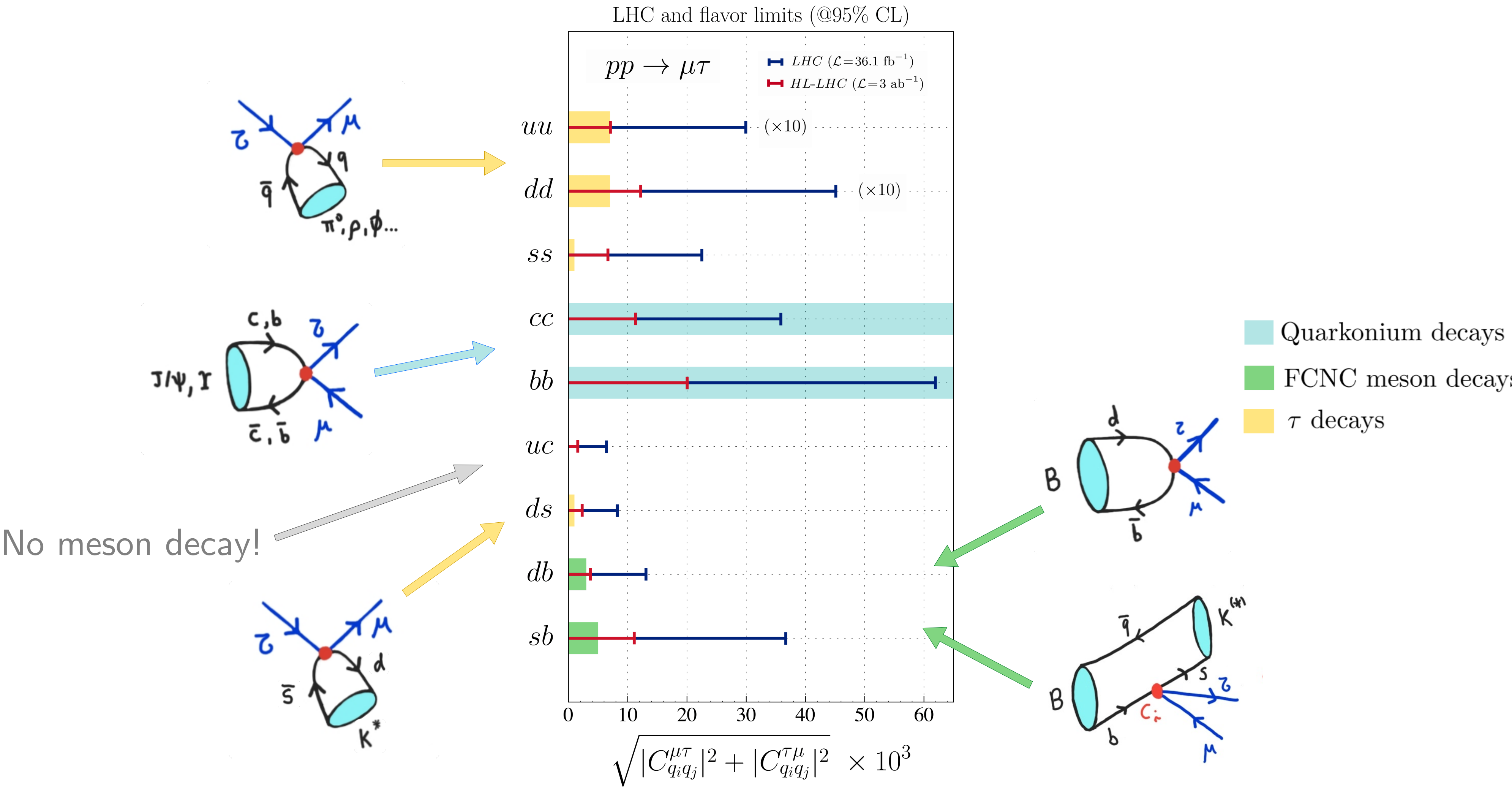

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[Angelescu, Faroughy, **OS**, '20]

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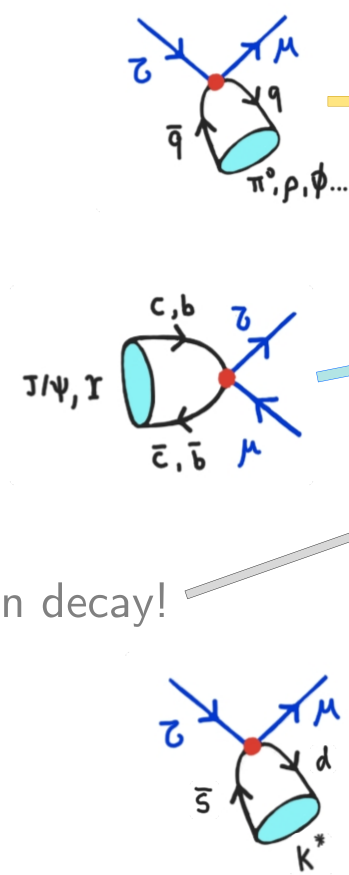
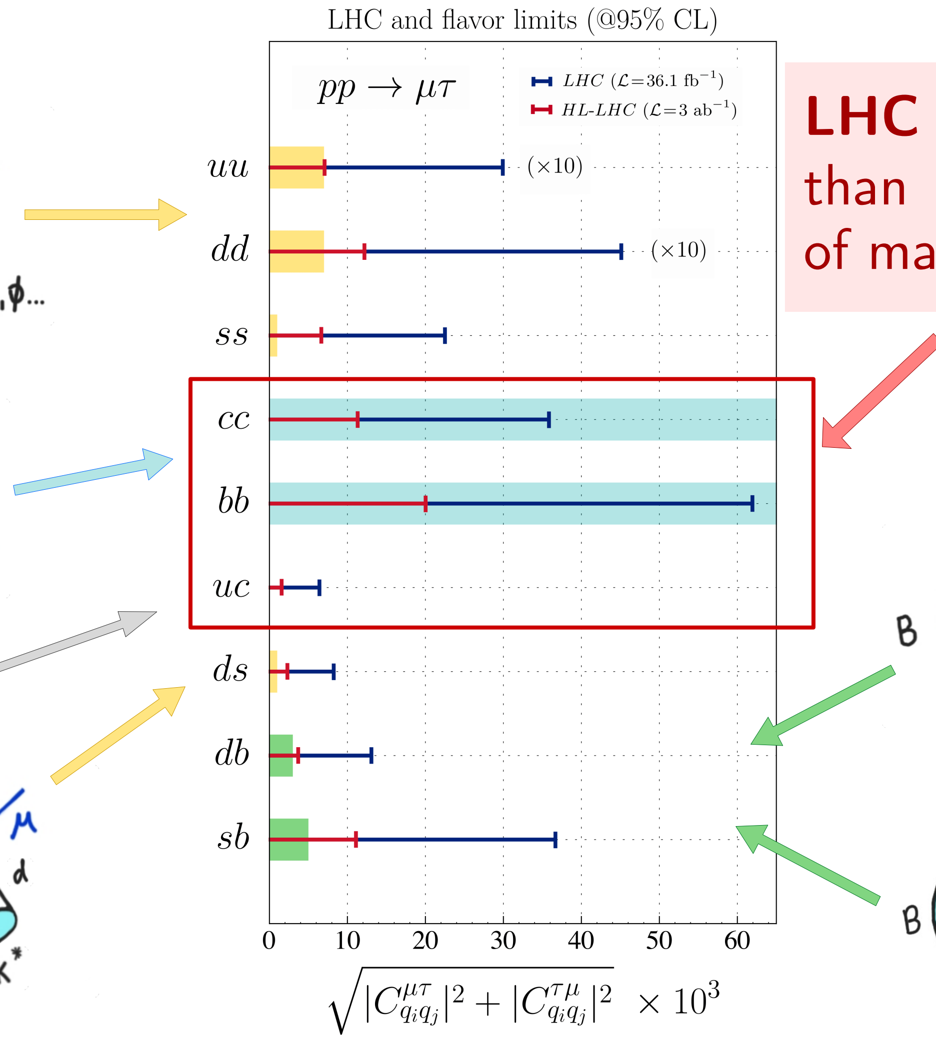
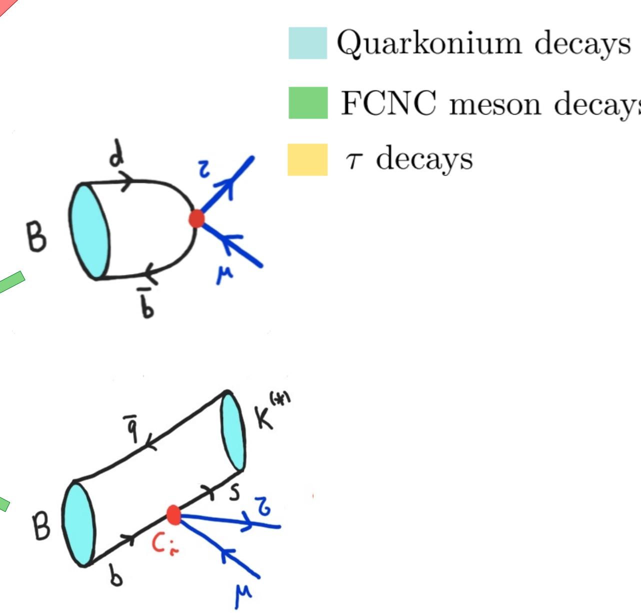




LHC limits **more constraining** than meson decays (by orders of magnitude)!



No meson decay!

See back-up for other channels.

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

Concrete examples:

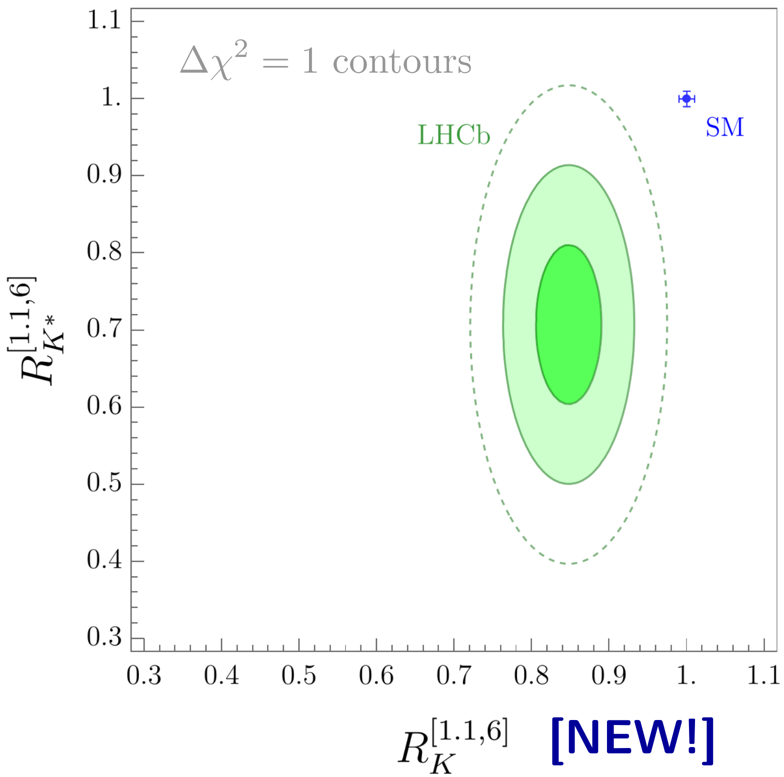
- **L**epton **F**lavor **V**iolation in meson decays
- Leptoquarks and **L**epton **F**lavor **U**niversality

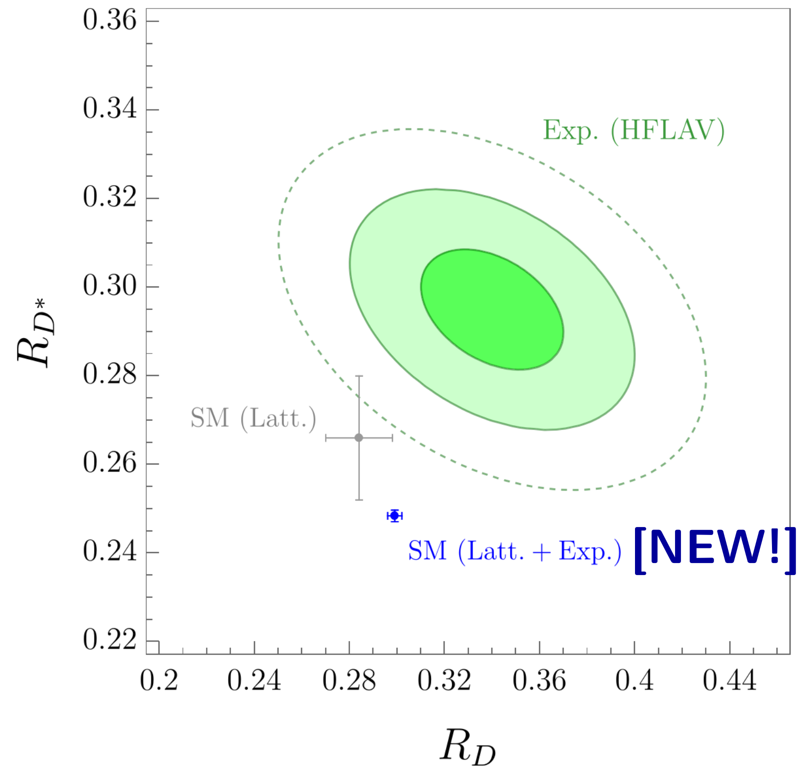
Example: Lepton Flavor Universality (LFU) violation

Several **discrepancies** have been observed in ***b*-hadron** decays $[\approx 4\sigma]$:

See talks by N. Mahmoudi and A. Gérardin

[LHCb, *B*-factories]





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

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

See also: R_{pK}

See also: $R_{J/\Psi}$

If confirmed with more data, it would imply **New Physics** at **O(few TeV)**!

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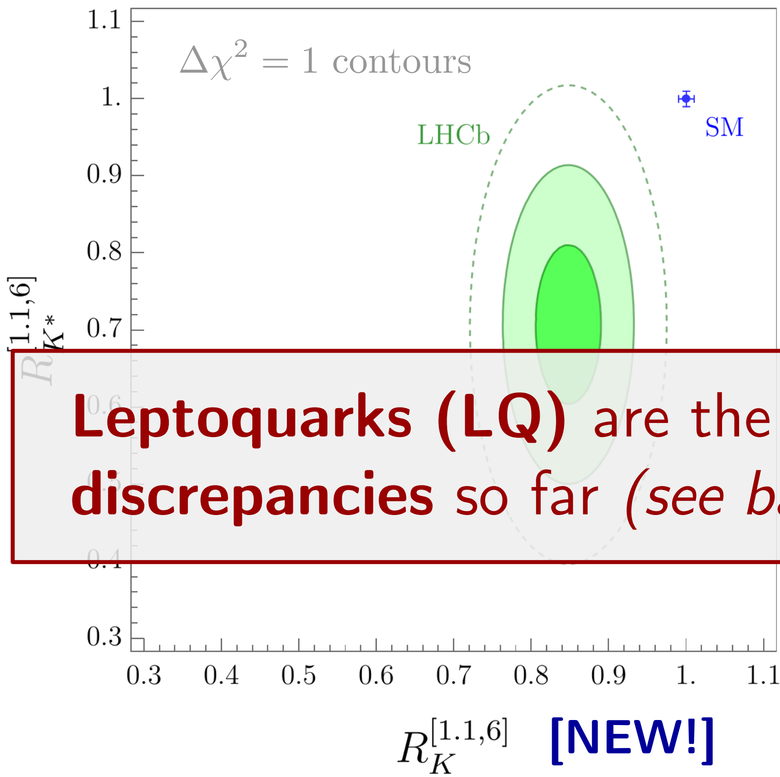
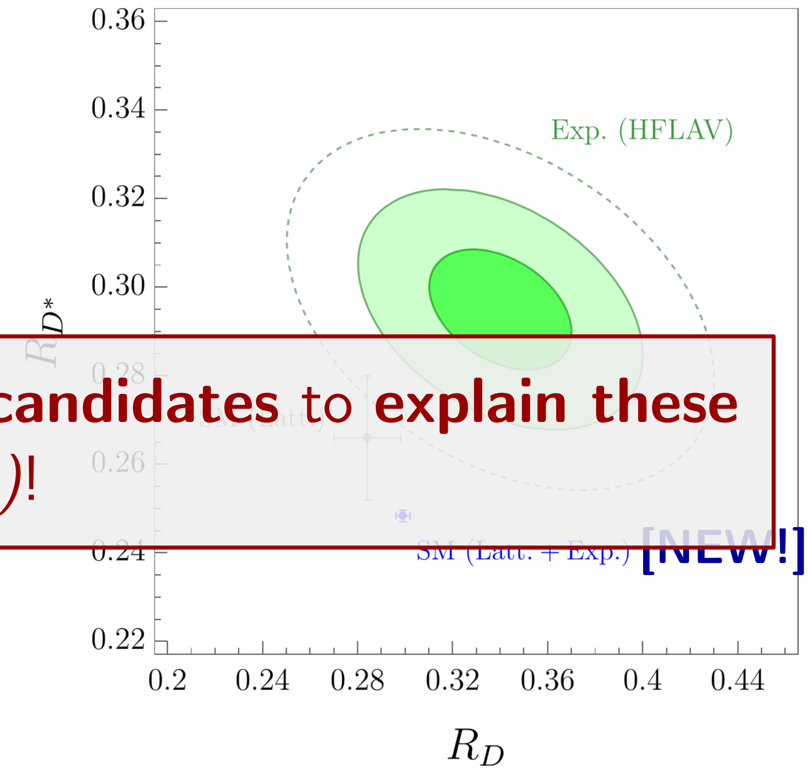


[NEW!]



[NEW!]

Leptoquarks (LQ) are the **best candidates** to **explain these discrepancies** so far *(see back-up)*!

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

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

See also: R_{pK}

See also: $R_{J/\Psi}$

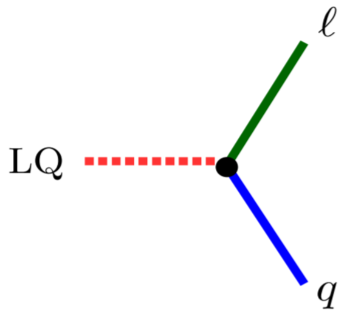
If confirmed with more data, it would imply **New Physics** at **O(few TeV)**!

Which leptoquark?

Few viable scenarios!

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

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



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

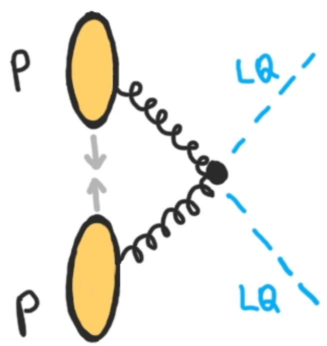
NB. *UV completion needed for vector leptoquarks (see back-up)!*

Direct searches at the LHC

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
see also [Borschensky et al. '20]

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]

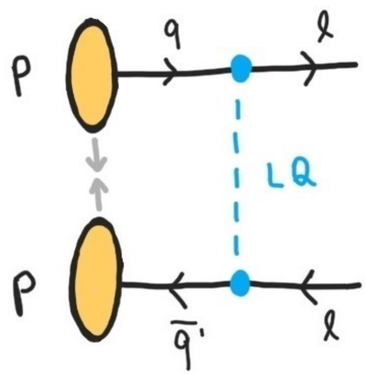
[Angelescu, Becirevic Faroughy, Jaffredo, **OS**, '21]

Useful results, but with **limited reach** (few TeV); **not enough** to **fully probe** the mass scales suggested by **flavor anomalies**!

LHC constraints

ii) di-lepton production at high-p_T

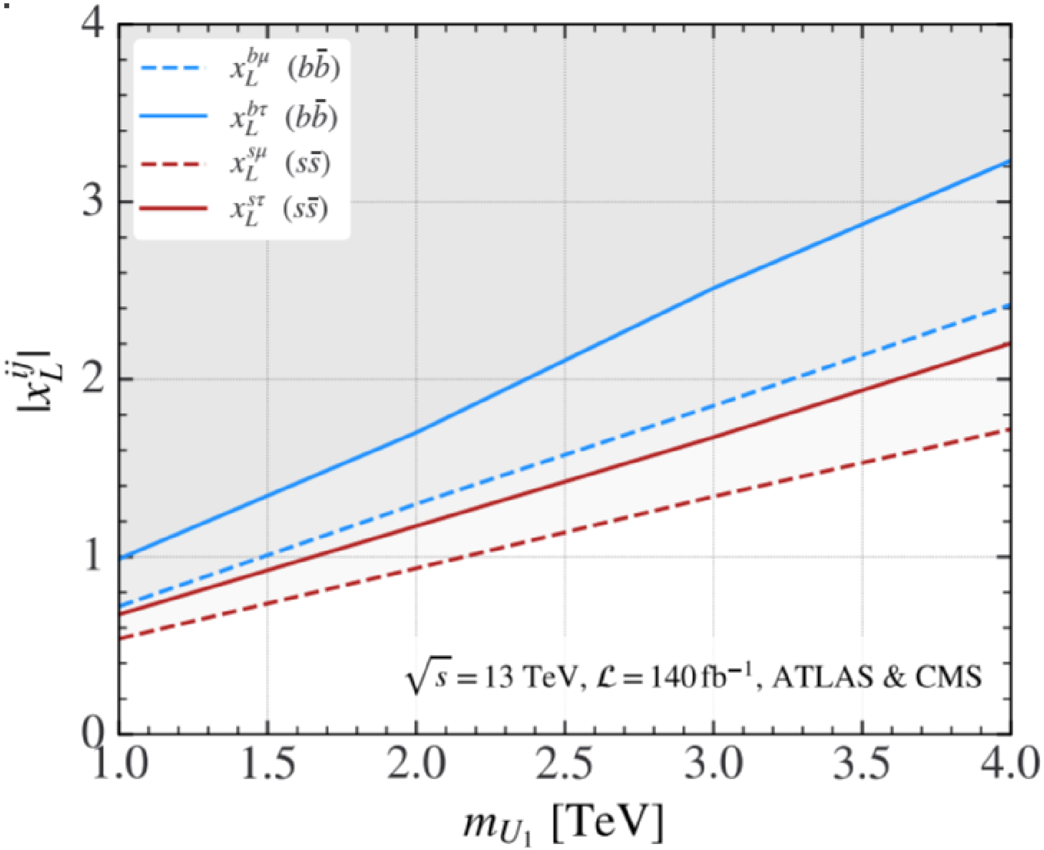
Useful upper limits on **LQ couplings**:



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]



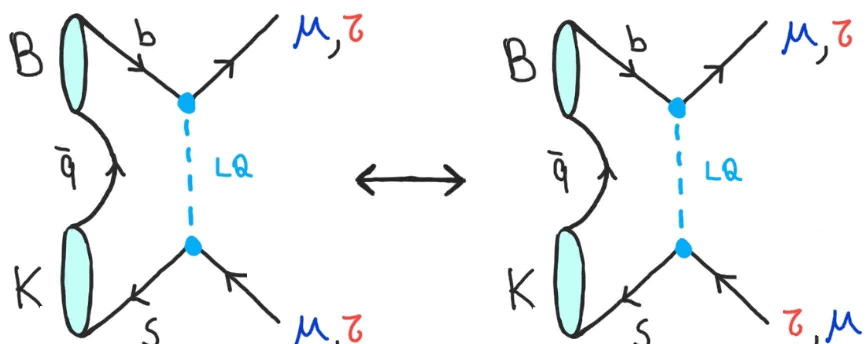
First computed by [Eboli, '88]

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

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]

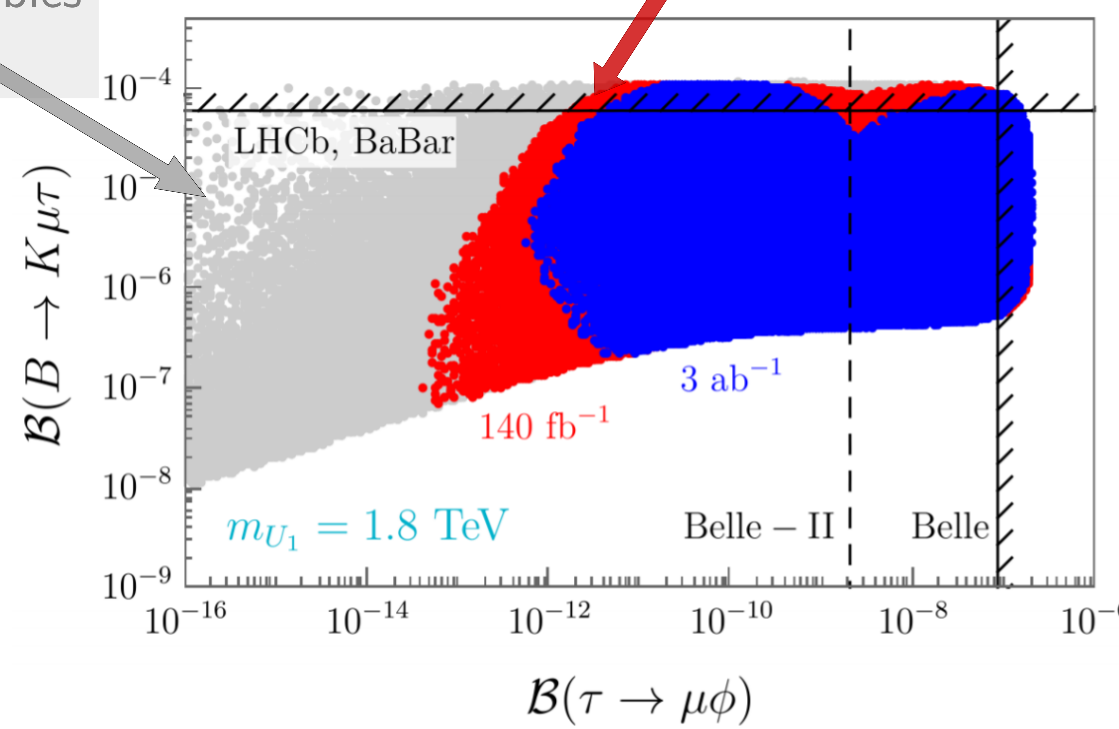
$$B_s \to \mu\tau \qquad B \to K^{(*)}\mu\tau$$

New searches $(95\%\,\mathrm{CL})$: [LHCb]

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

Several flavor observables (at tree-level)

LHC constraints



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

Perspectives

Perspectives

EFTs at LHC

- If NP lies beyond the LHC reach, measuring the high-energy tails of dilepton distributions would offer the best opportunity to probe these scenarios.

  Work in progress to combine LHC and flavor constraints in full generality.

- Assessing the validity of the EFT approach is needed (when LHC data is not precise enough).

  Ongoing activity e.g. at the EFT @ LHC working group.

B-physics

- Excellent example of the complementarity of low and high-energy observables!
- Many awaited exp. results can clarify the situation – mostly LHCb and Belle-II, but also CMS and ATLAS:

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

- If anomalies are confirmed in the future, unique opportunity to use exp. data to build a model of New Physics!

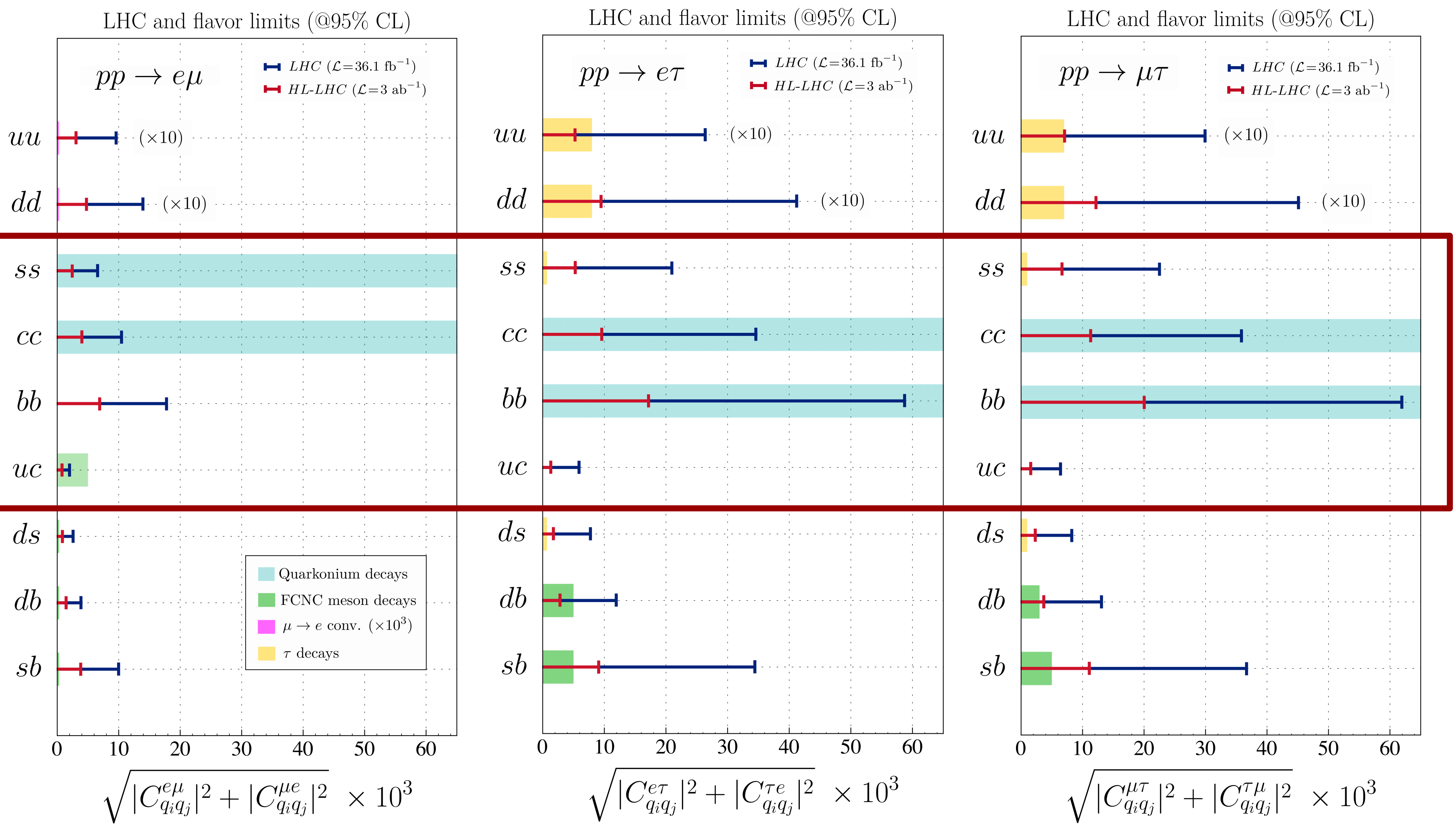
Exchange between theory and experiment is fundamental!

Thank you!

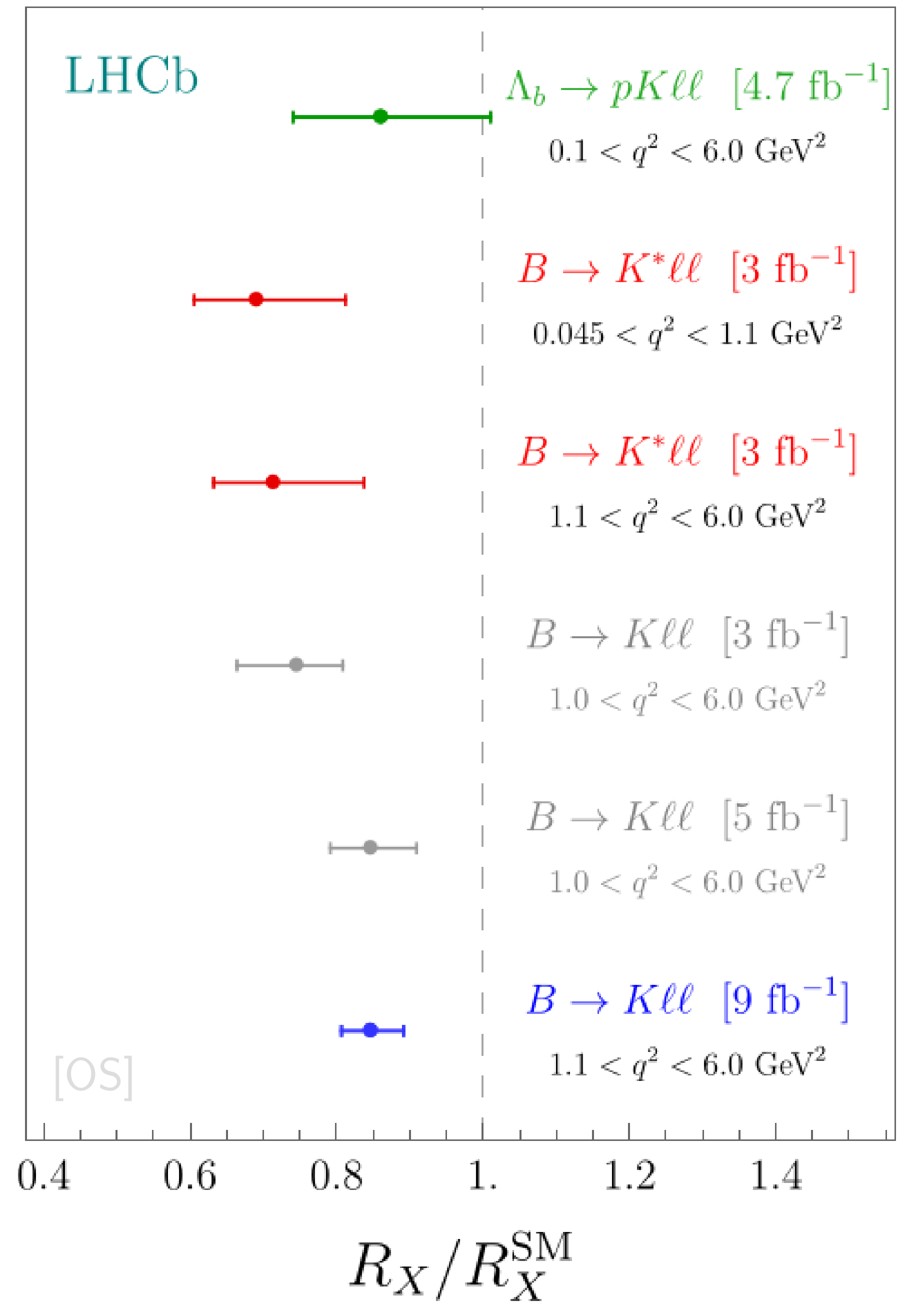
Back-up

Our results: $e\mu$, $e\tau$, $\mu\tau$

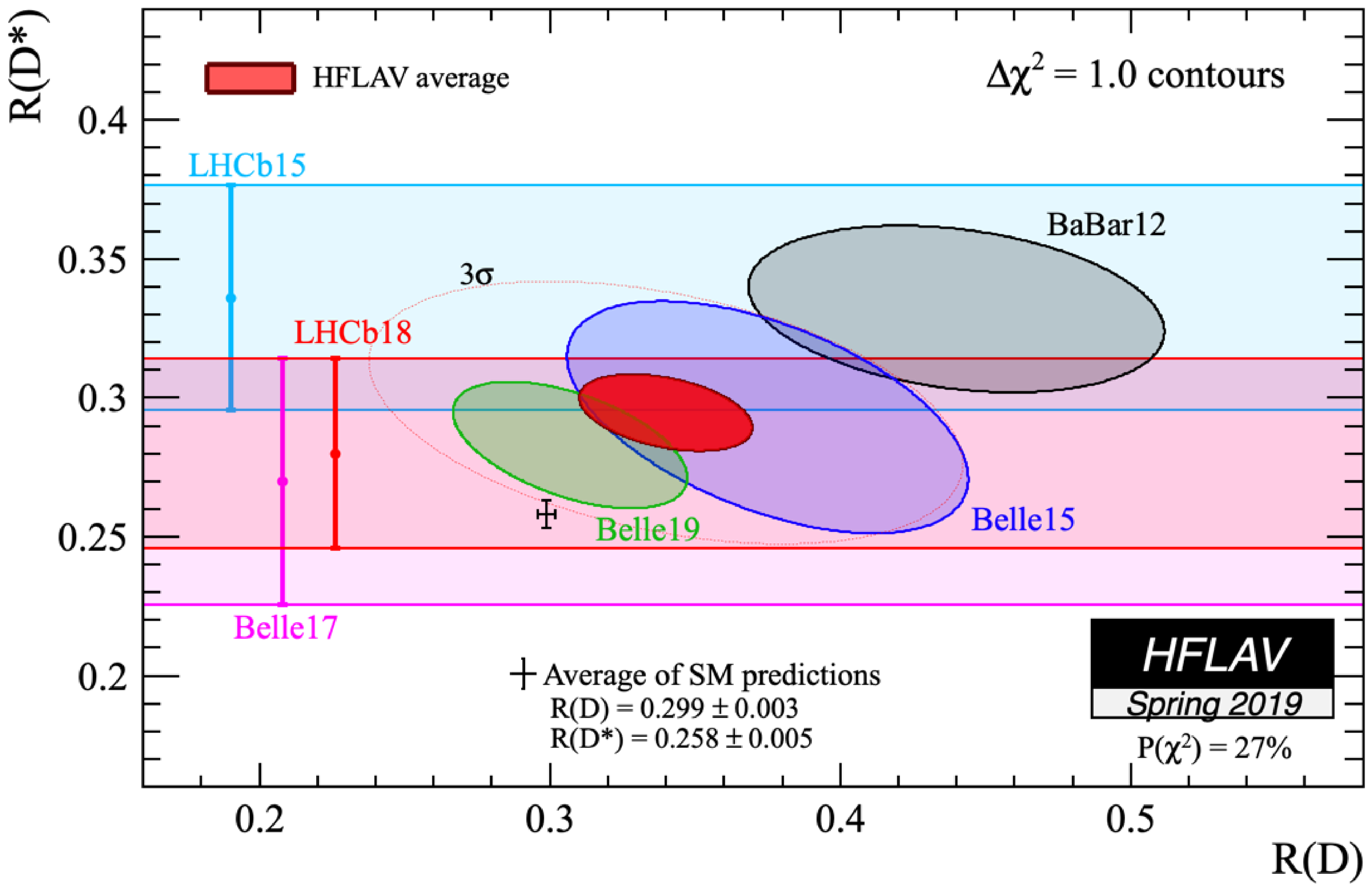
$$O_{VLL}^{ijkl} = \left(\bar{q}_{Li}\gamma^{\mu}q_{Lj}\right)\left(\bar{\ell}_{Lk}\gamma_{\mu}\ell_{Ll}\right)$$



LHC data is **more constraining** for **flavor-conserving** transitions (ss, cc and bb), as well as for the **charm sector** (cu).



LHCb
$\Lambda_b \to pK\ell\ell$ [4.7 fb^{-1}]
$0.1 < q^2 < 6.0$ GeV^2
$B \to K^*\ell\ell$ [3 fb^{-1}]
$0.045 < q^2 < 1.1$ GeV^2
$B \to K^*\ell\ell$ [3 fb^{-1}]
$1.1 < q^2 < 6.0$ GeV^2
$B \to K\ell\ell$ [3 fb^{-1}]
$1.0 < q^2 < 6.0$ GeV^2
$B \to K\ell\ell$ [5 fb^{-1}]
$1.0 < q^2 < 6.0$ GeV^2
$B \to K\ell\ell$ [9 fb^{-1}]
$1.1 < q^2 < 6.0$ GeV^2
[OS]
0.4
0.6
0.8
1.
1.2
1.4
$R_X / R_X^{\rm SM}$



R(D*)
HFLAV average
$\Delta\chi^2 = 1.0$ contours
LHCb15
LHCb18
BaBar12
3σ
Belle19
Belle15
Belle17
Average of SM predictions
R(D) = 0.299 ± 0.003
R(D*) = 0.258 ± 0.005
HFLAV
Spring 2019
$P(\chi^2) = 27\%$
0.4
0.35
0.3
0.25
0.2
0.2
0.3
0.4
0.5
R(D)

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

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

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

[Buchmuller, Wyler. '85]

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

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

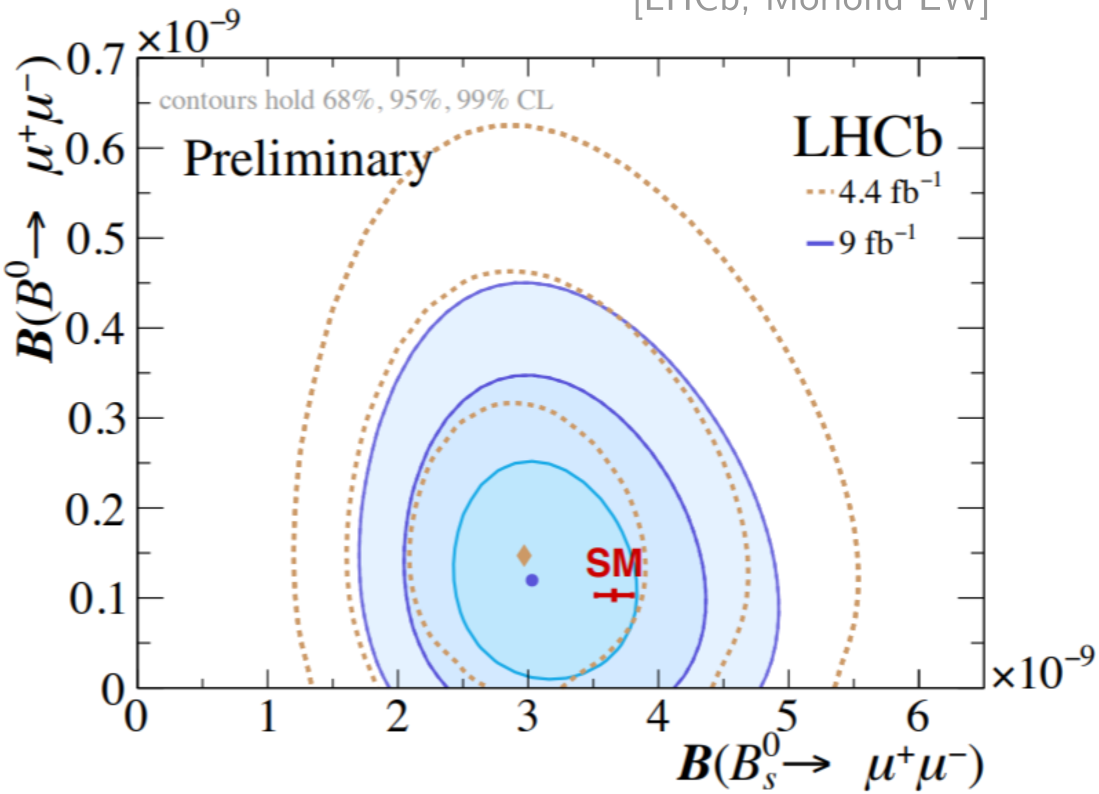
[Our average, CMS, ATLAS, LHCb]

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

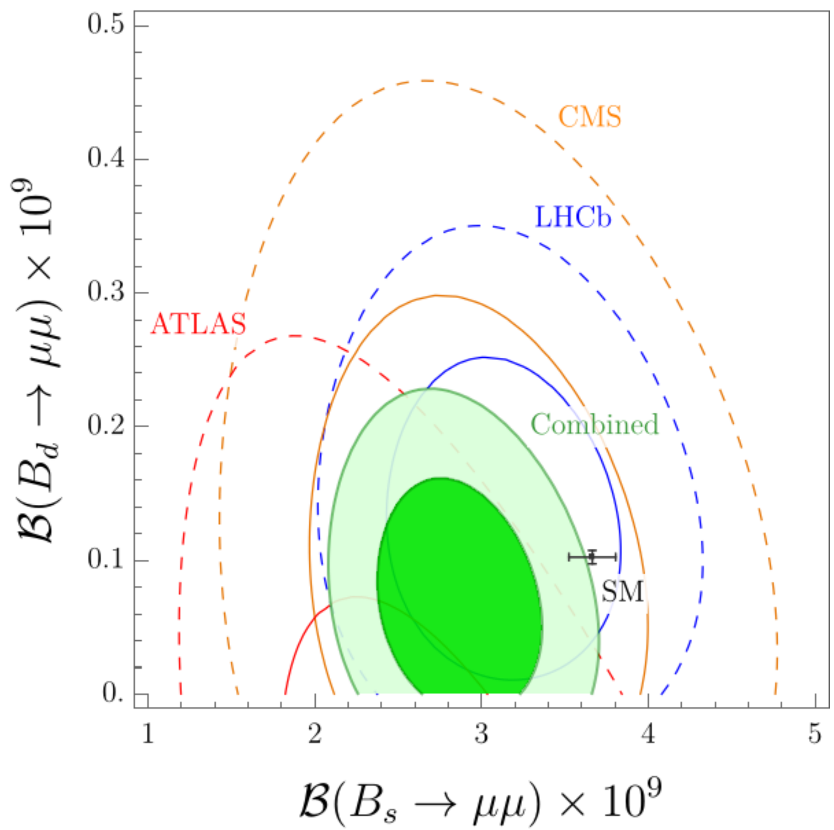
[Beneke et al. '19]

Latest LHCb results

[LHCb, Moriond EW]



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



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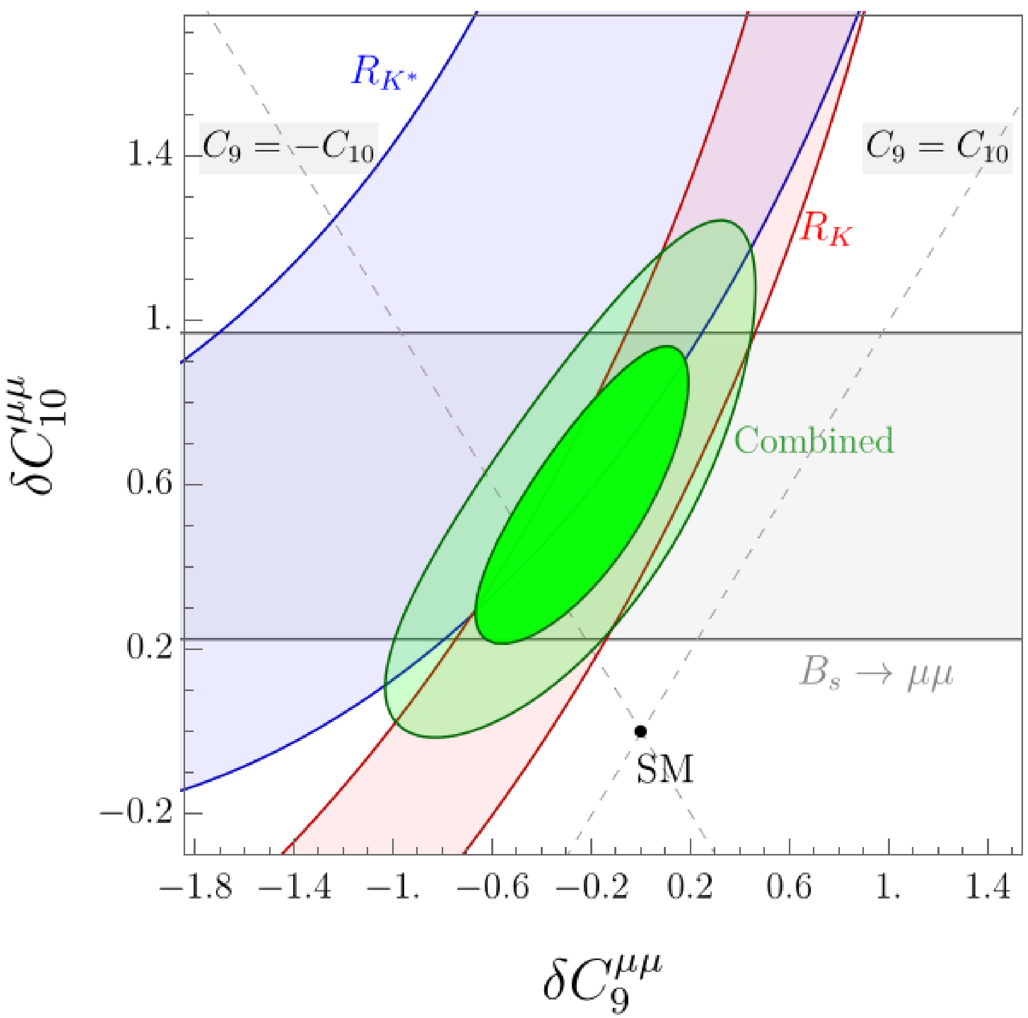
[Our average, CMS, ATLAS, LHCb]

[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

Concrete models for R_K & R_{K^*}

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

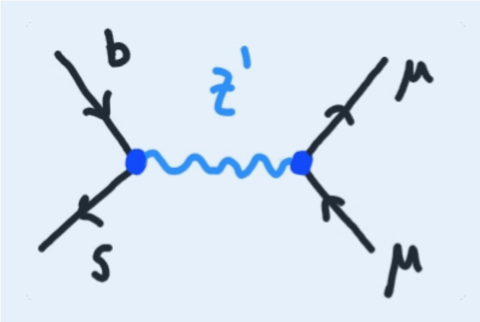
$$O_{lq}^{(1)} = (\overline{L}\gamma^\mu L)(\overline{Q}\gamma_\mu Q)$$

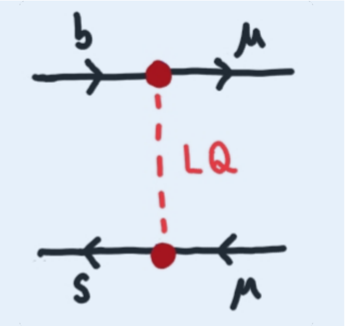
$$O_{lq}^{(3)} = (\overline{L}\gamma^\mu \tau^I L)(\overline{Q}\gamma_\mu \tau^I Q)$$

NB. LFU breaking operators!

- Tree-level mediators:

$$\frac{g_{\rm NP}}{\Lambda} \approx \frac{1}{50 \text{ TeV}}$$





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

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

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

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

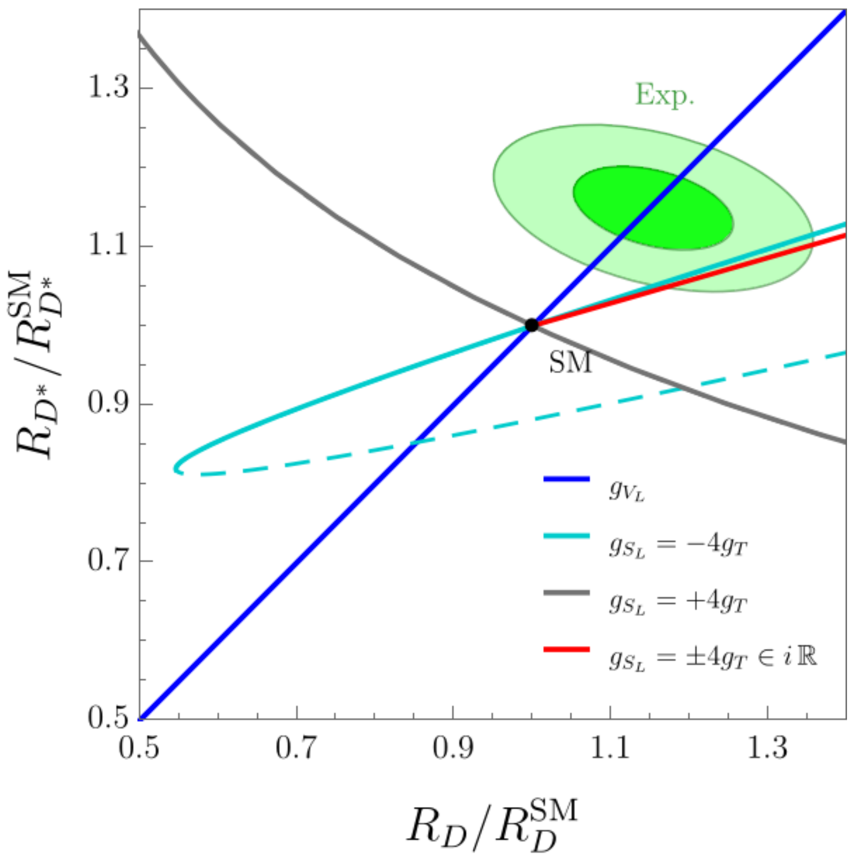
  $\Rightarrow$ e.g. $g_{V_L} \in (0.05,\, 0.09)$, **but not only**!

[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 $g_{S_L} = \pm 4\, g_T$

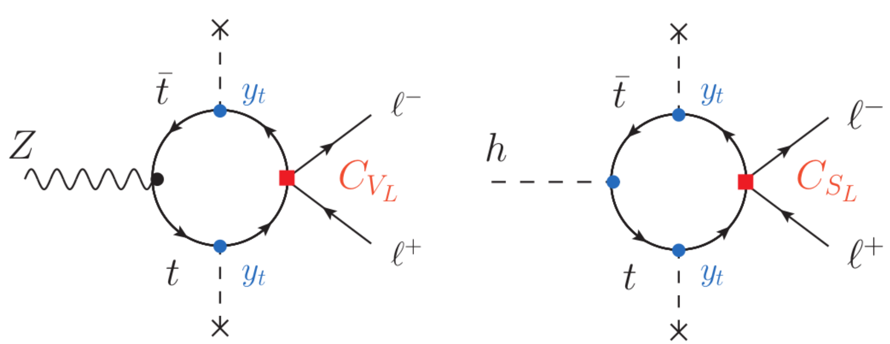
More **exp. information** is **needed**:

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

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

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

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



Electroweak observables can also be a useful handle!

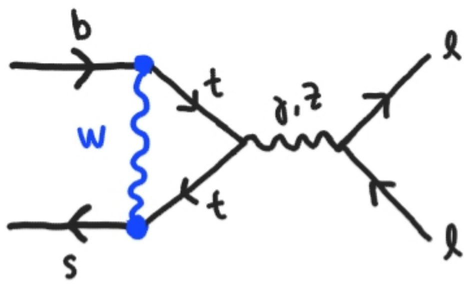
[Feruglio et al. '17]

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

From EFTs to concrete models

EFT interpretations:

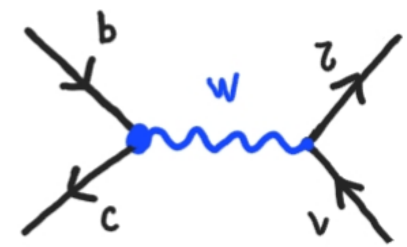
[Angelescu, Becirevic Faroughy, Jaffredo, **OS**, '21]



$$\mathcal{L}_{\rm eff} \supset \frac{1}{\Lambda_{R_K}^2}(\bar{s}_L\gamma^\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L) + \text{h.c.}$$

with $\Lambda_{R_K} \approx 30~\text{TeV}$

e.g.



$$\mathcal{L}_{\rm eff} \supset -\frac{1}{\Lambda_{R_D}^2}(\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L) + \text{h.c.}$$

$\Lambda_{R_D} \approx 3~\text{TeV}$

Challenges for New Physics:

See talk by N. Mahmoudi

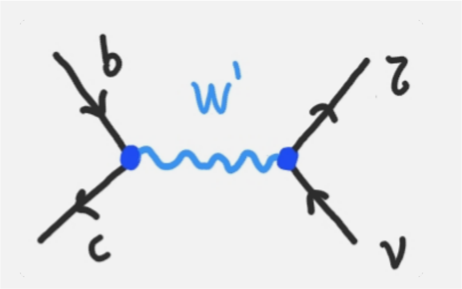
- Flavor observables: *e.g.* Δm_{B_s} *and* $B \to K^{(*)}\nu\bar{\nu}$
- Radiative constraints: *e.g.* $\tau \to \mu\nu\bar{\nu}$ *and* $Z \to \ell\ell$ [Feruglio et al. '16]
- LHC direct and indirect bounds. [Greljo et al. '15, Faroughy et al. '16, ...]

Scalar and vector **leptoquarks (LQ)** are the **best candidates** so far

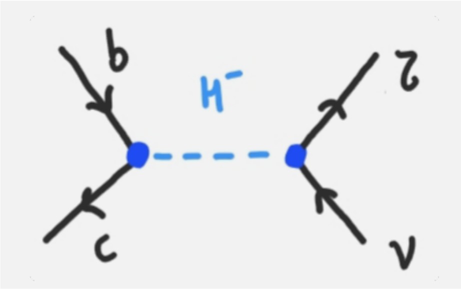
Explaining $b \to c\tau\bar{\nu}$

- $R_{D^*}^{\rm exp} > R_{D^*}^{\rm SM}$ require new bosons at $\Lambda_{\rm NP} \lesssim 5$ TeV .

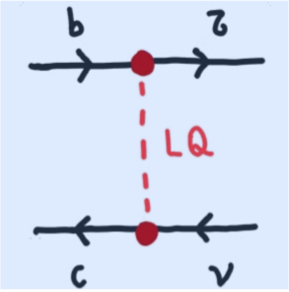
- Possible **tree-level mediators**:



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



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



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

- **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]

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

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]

- $SU(4) \times SU(3)' \times SU(2)_L \times U(1)' \rightarrow \mathcal{G}_{\rm SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$
- 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: $[\rm PS]^3 = [SU(4) \times SU(2)_L \times SU(2)_R]^3$ [Bordone et al. '17]

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

B-decays with missing energy

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

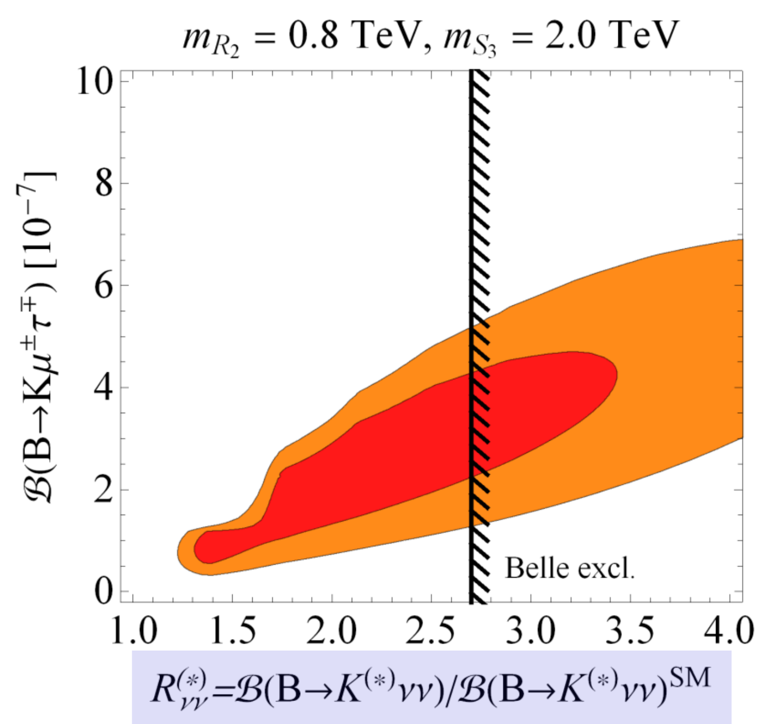
- **Clean observable** in the SM:

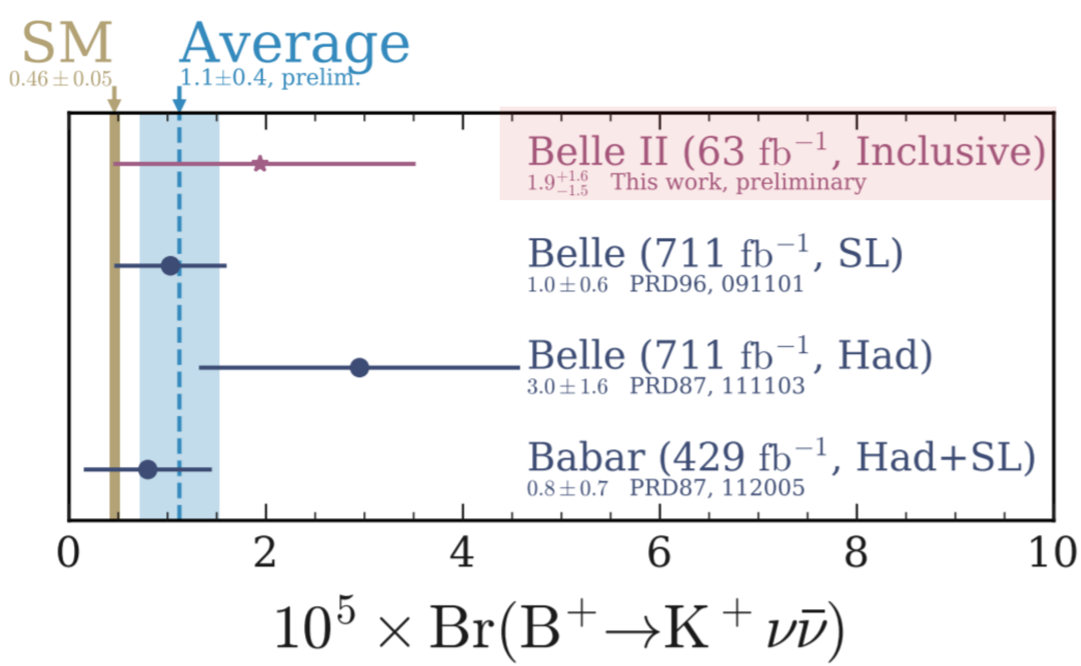
$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})^{\rm SM} = 4.6(5) \times 10^{-6}$$

[Blake et al. 1606.00916]

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

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

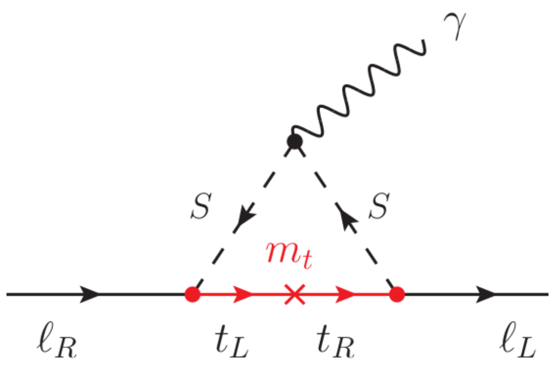




Promising results from early **Belle-II data**!

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
$\widetilde{R}_2$	$(\mathbf{3}, \mathbf{2}, 1/6)$	$\bar{d}_R L$	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]

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

$\Longrightarrow$ 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...)