Rare decays and tests of conservation laws in charm and B-decays

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IJCLab (Orsay)

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Outline

I. Introduction:

- Seeking New Physics through flavor

II. Lepton Flavor Universality:

- B-anomalies: where do we stand?
- LFU tests in D-meson decays
- EFT interpretations
- From EFT to concrete models

III. Closing the leptoquark window

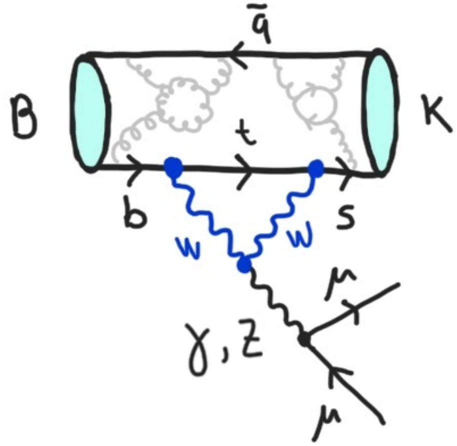
- LFV in B-meson decays

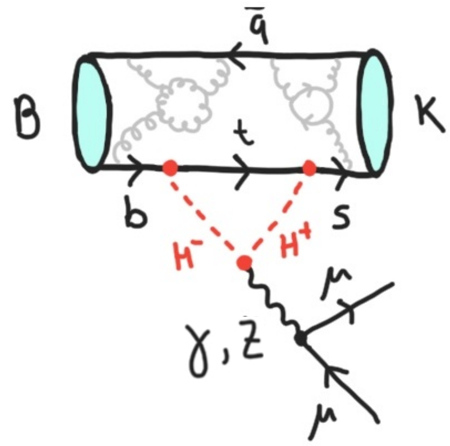
IV. Summary

Indirect Searches of New Physics

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

e.g.





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

Both th. and exp. must be precise!

Look for observables:

- (Highly) sensitive to contributions of physics beyond the SM
- Mildly (or not) sensitive to hadronic uncertainties
- Accessible in current and/or (near) future experiments.

NB. LFU observables are an excellent example!

Indirect Searches of New Physics

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

Global symmetry of 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

$$U(1)_B \times \underbrace{U(1)_e \times U(1)_\mu \times U(1)_\tau}_{\text{broken by } m_\nu \text{ !}}$$

Examples:

- Proton decay **(BNV)**: $p \to \pi^0 e^+$
- $0\nu\beta\beta$ **(LNV)**: $(A, Z) \to (A, Z+2) + 2e^-$
- Lepton Flavor Violation **(LFV)**: $\mu \to e\gamma$

Very clean probes of New Physics!

Lepton Flavor Universality

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:

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

R_{pK}

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

$R_{J/\Psi}$

[LHCb, *B*-factories]

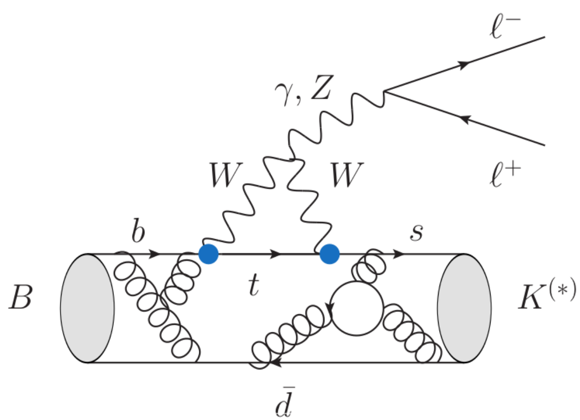
- **If confirmed** with more data, they will be a clear evidence of **New Physics**.

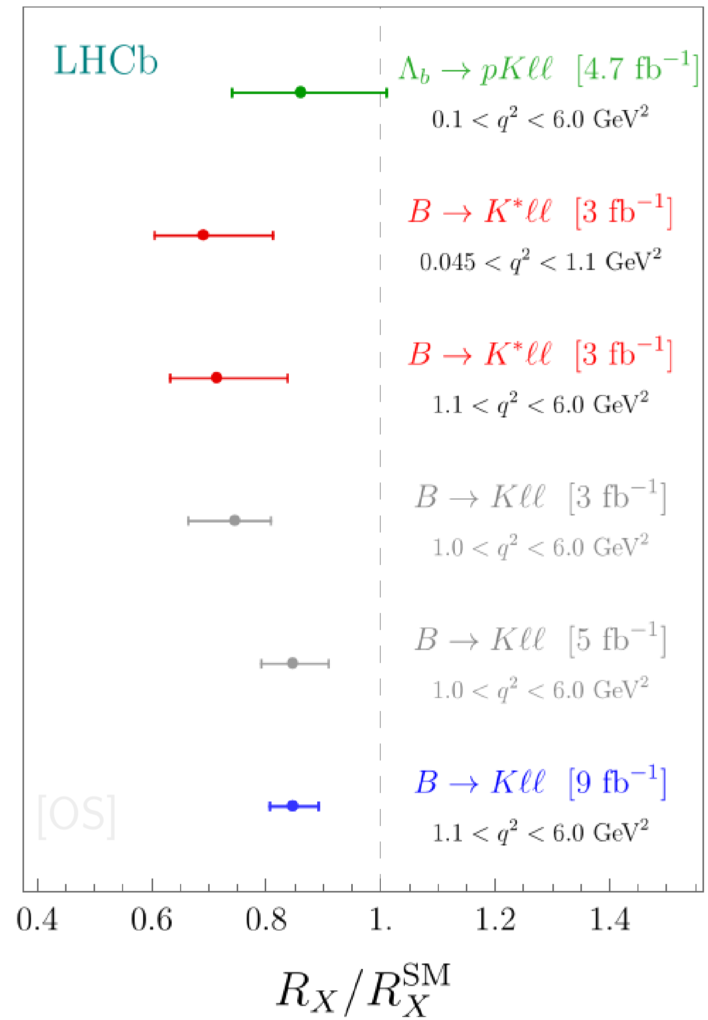
LFU in $b \to s\ell\ell$

See talks by Mannel, Watanuki

Experiment

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





Theory (loop-induced):

- Hadronic uncertainties almost fully cancel. [Hiller, Kruger. '04]

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

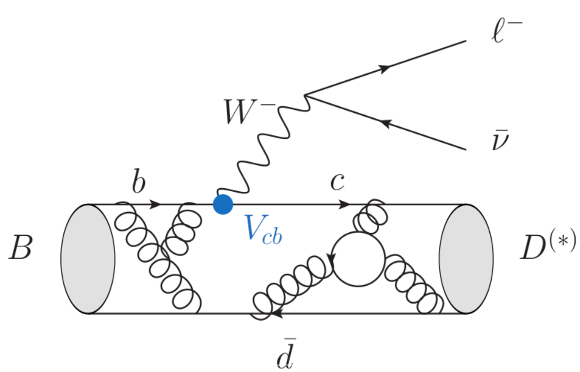
- However, QED corrections important, $R_K^{SM} = 1.00(1)$ [Isidori et al. '20]

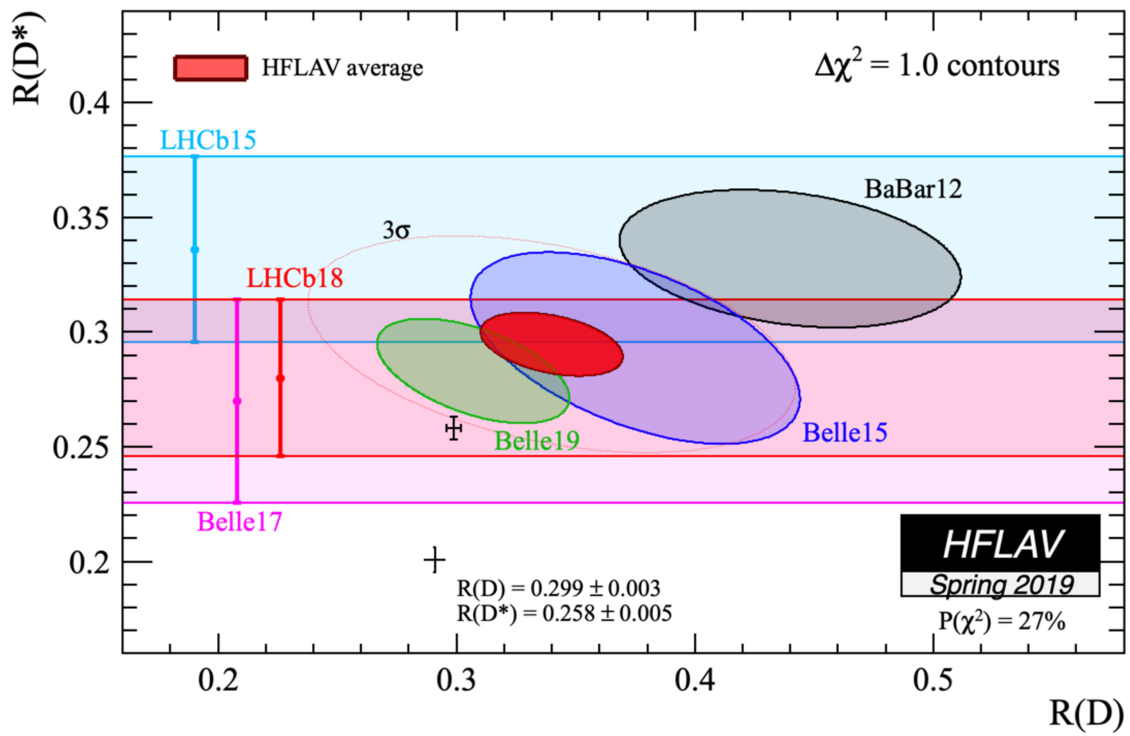
LFU in $b \to c\ell\bar{\nu}$

See talk by Basith

Experiment

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





- $R_D^{\rm exp}$ and $R_{D^*}^{\rm exp}$: **dominated by BaBar**.
- LHCb confirmed tendency $R_{J/\psi}^{\rm exp} > R_{J/\psi}^{\rm SM}$, 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

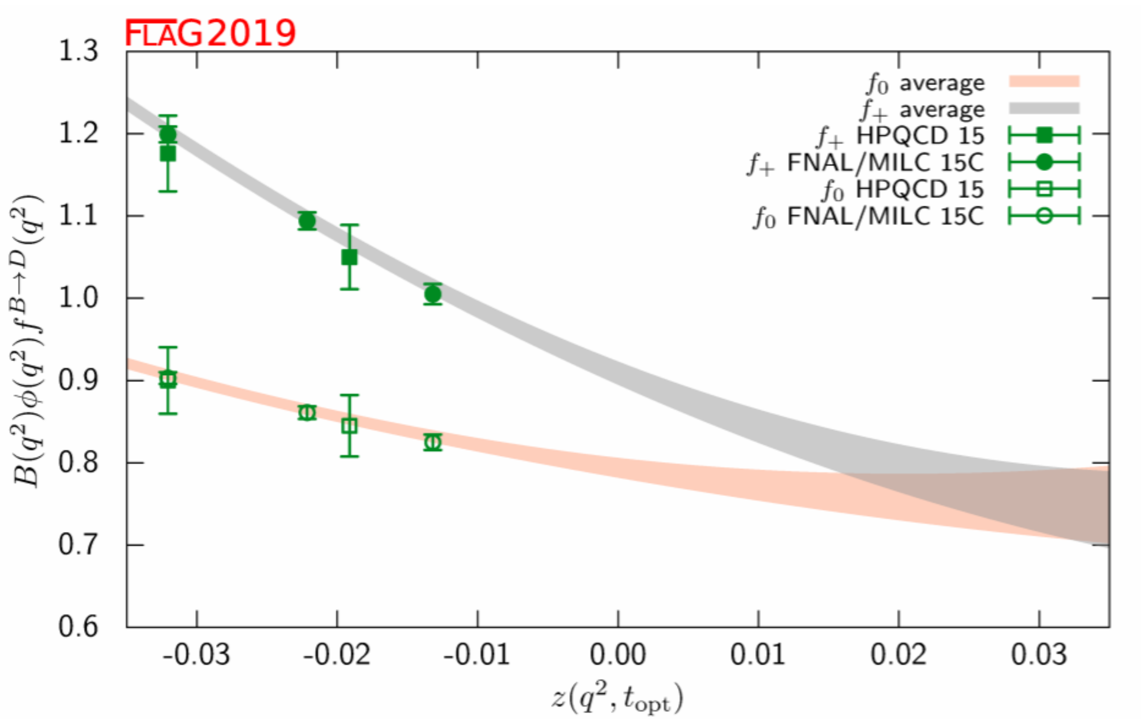
See talk by Kaneko

- 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]



FLAG average:

$$R_D^{\rm SM} = 0.300(8)$$

SM predictions

[circa '20]

Form-factors: R_{D^*}

See talk by Kaneko

- Use the $B \to D^*(D\pi)l\bar{\nu}$ $(l = e, \mu)$ angular distributions measured at the 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?).

SM predictions

[circa '20]

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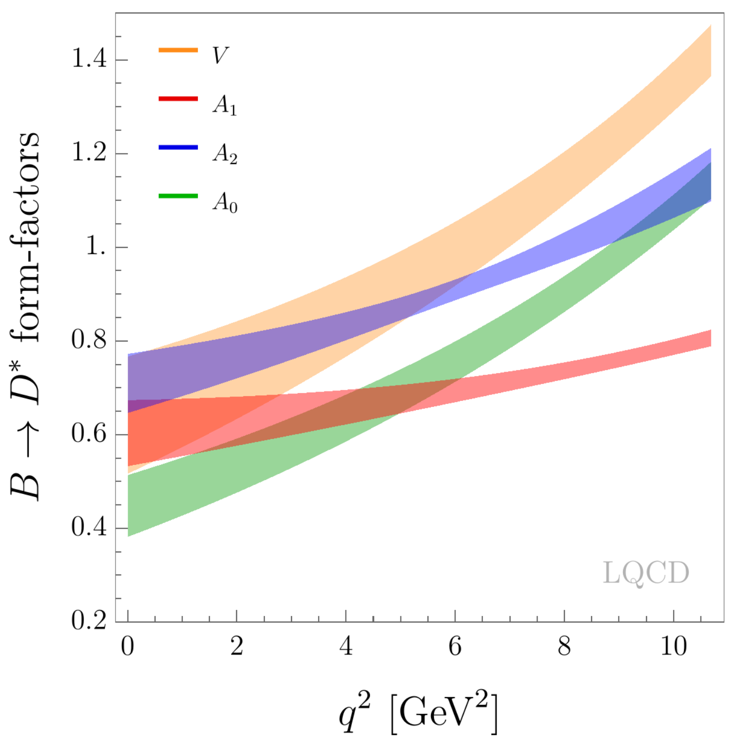
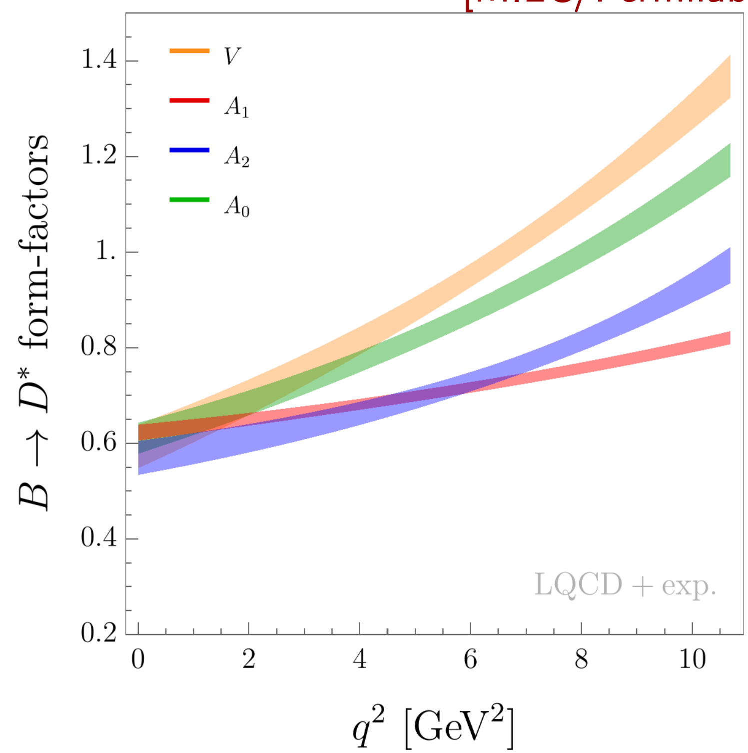
- First lattice QCD computation at $q^2 \neq q^2_{\mathrm{max}}$ $(w \neq 1)$:

[NEW! '21]

[MILC/Fermilab, 2105.14019]





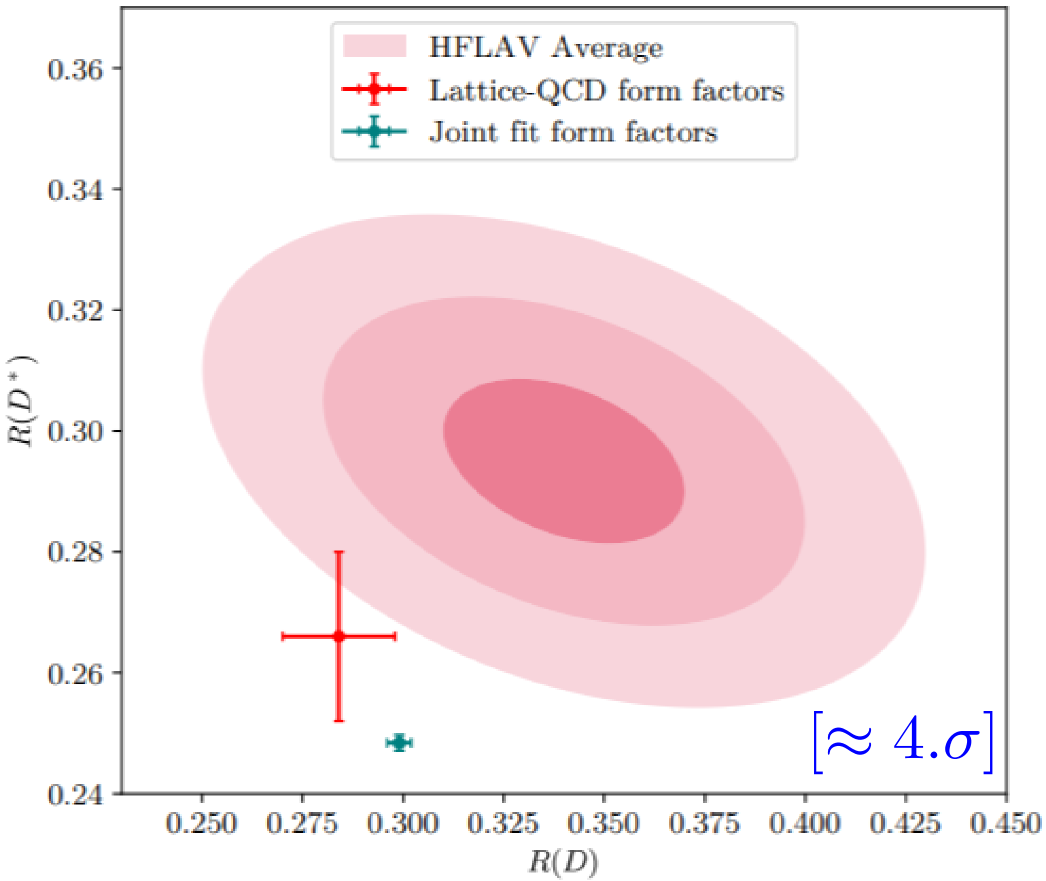
NB. See also [Harrison et al., 2105.11433] for $B_s \to D_s^*$ form-factors

SM predictions

Form-factors: R_{D^*}

[NEW! '21]

[MILC/Fermilab, 2105.14019]



HFLAV:	$R_{D^*}^{\rm SM} = 0.258(3)$

Lattice:	$R_{D^*}^{\rm SM} = 0.266(14)$
Lattice+exp:	$R_{D^*}^{\rm SM} = 0.2484(13)$

- Discrepancy confirmed by lattice QCD!
- Combined fit of form-factors to lattice and exp. data lowers central value.

See [Bobeth et al. 2104.02094] about potential inconsistencies in Belle 2018 data .

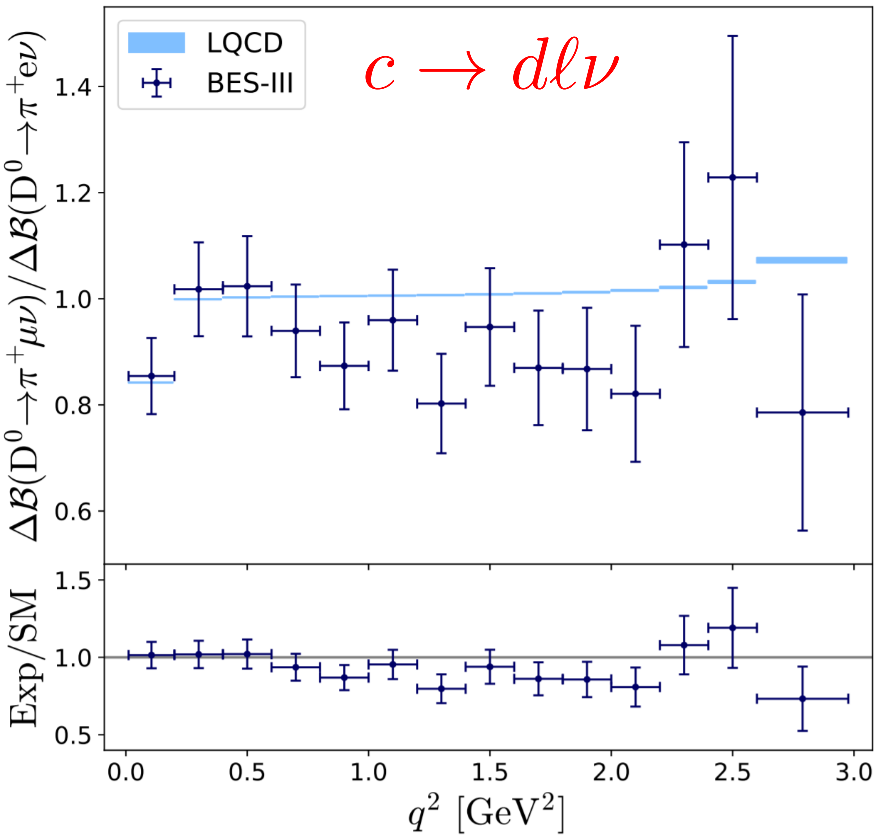
LFU tests in charm decays

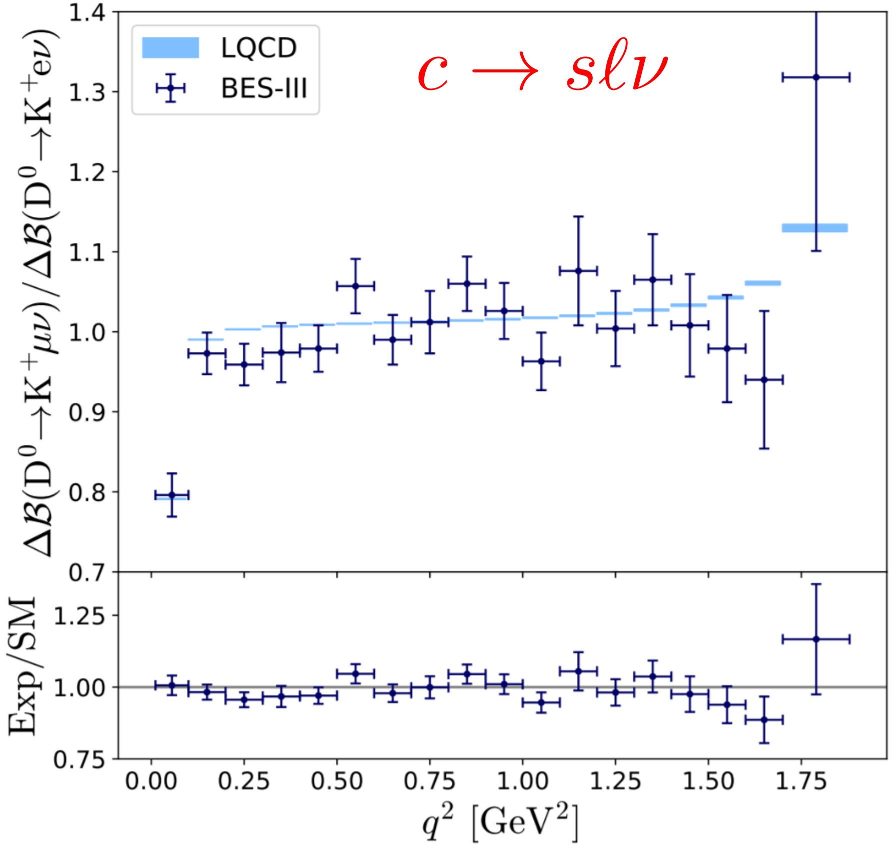
[Becirevic, Jaffredo, Penuelas, **OS**. '20]

- Good agreement between theory and experiment:

[see talk by Bai-Cian KE]

Form factors from [Lubicz et al. '19, '20]





$$R_{D\pi}^{(\mu/e)} = \frac{\mathcal{B}(D \to \pi \mu \bar{\nu})}{\mathcal{B}(D \to \pi e \bar{\nu})}$$

$$R_{DK}^{(\mu/e)} = \frac{\mathcal{B}(D \to K \mu \bar{\nu})}{\mathcal{B}(D \to K e \bar{\nu})}$$

LFU tests in charm decays

See talks by Xiang Pan, Bai-Cian KE

- LFU is also well tested in leptonic decays,

[BES-III, 2106.02218]

$$R_{D_s}^{(\tau/\mu)} = \frac{\mathcal{B}(D_s \to \tau\nu)}{\mathcal{B}(D_s \to \mu\nu)} \overset{\text{exp}}{=} 9.72(37)$$

vs. $\left[\overset{\text{SM}}{=} 9.75 \right]$

[BES-III, 1908.08877]

$$R_{D}^{(\tau/\mu)} = \frac{\mathcal{B}(D \to \tau\nu)}{\mathcal{B}(D \to \mu\nu)} \overset{\text{exp}}{=} 3.21(77)$$

vs. $\left[\overset{\text{SM}}{=} 2.67 \right]$

$\Longrightarrow$ Provide useful constraints on NP scenarios (in particular, if *pseudoscalar operators* are present).

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

[Fleischer et al. '19]

See talk by S. Fajfer for more charm observables!

NB. For the complementarity with LHC bounds, see [Fuentes-Martin et al. '20]

EFT interpretations

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

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

- **Semileptonic operators**:

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

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

- 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

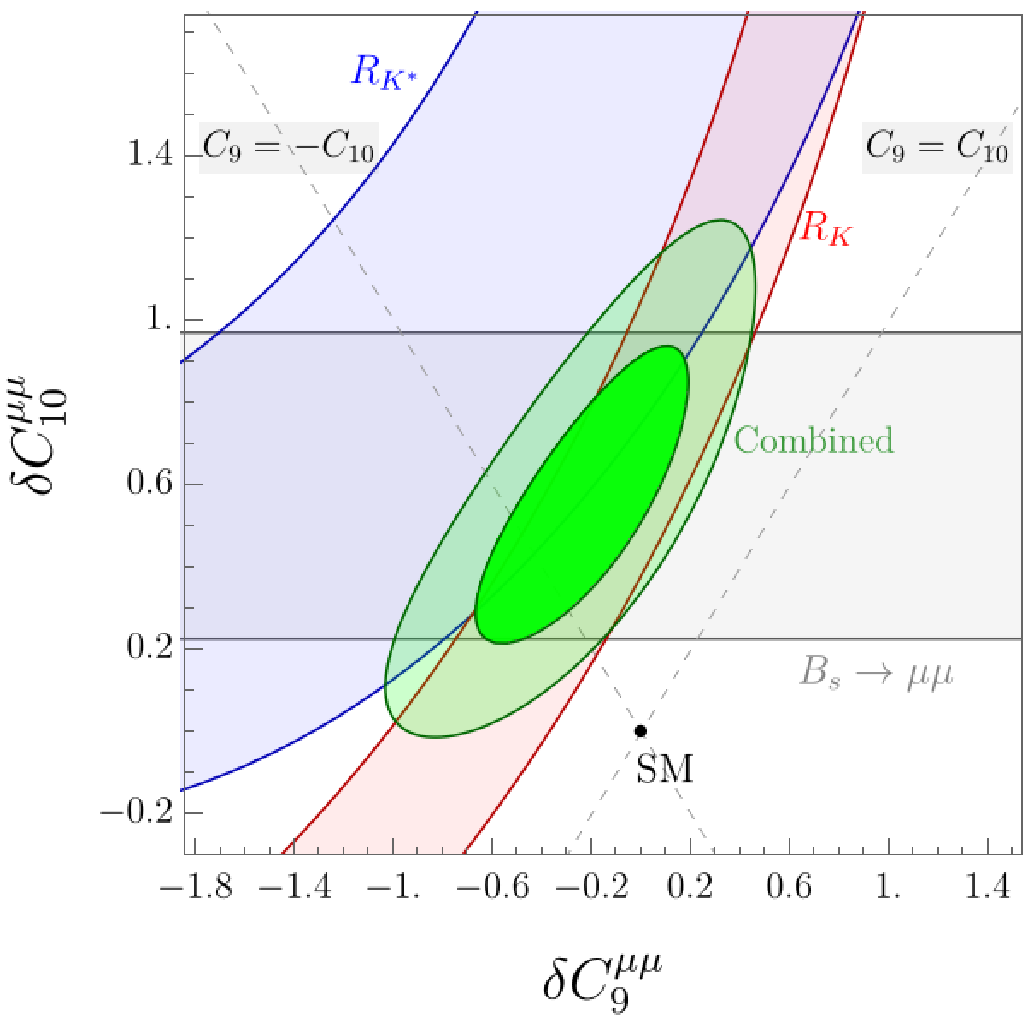
$$\overline{B}(B_s \to \mu\mu)^{\rm exp} = (2.85 \pm 0.22) \times 10^{-9}$$ [Our average, CMS, ATLAS, LHCb]

$$\overline{B}(B_s \to \mu\mu)^{\rm SM} = (3.66 \pm 0.14) \times 10^{-9}$$ [Beneke et al. '19]

Combined fit

[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 $R_{K^*}^{\text{exp}} < R_{K^*}^{\text{SM}}$
- Purely **left-handed** operator preferred $[4.6\sigma]$:

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

[See talk by J. Virto]

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

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. $g_{V_L} \in (0.06,\, 0.11)$, **but not only**!

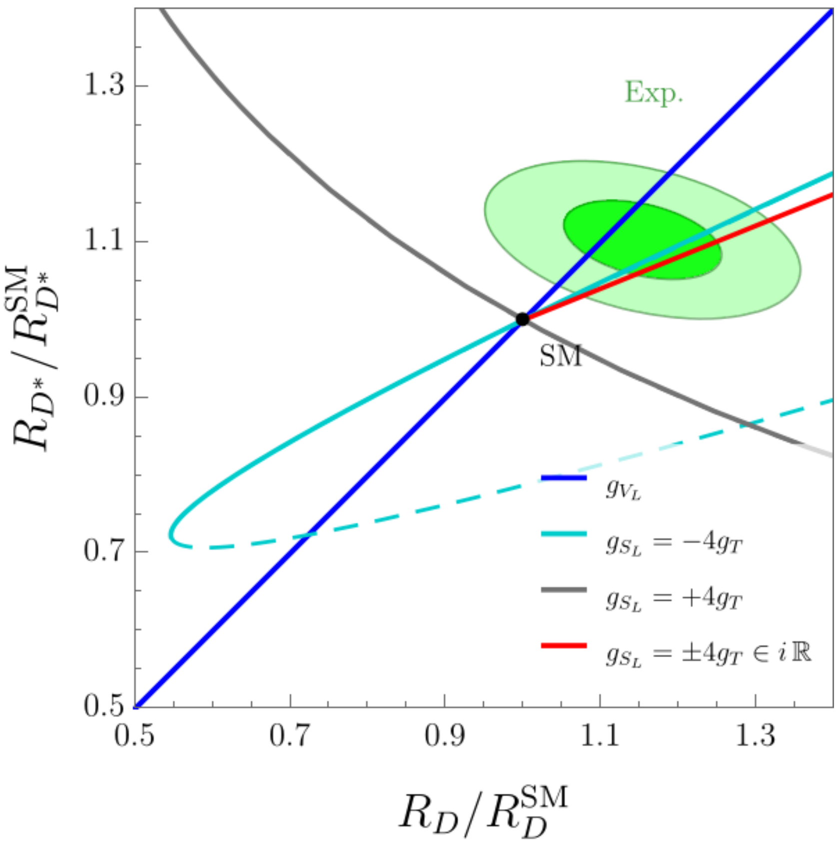
[Angelescu, Becirevic Faroughy, Jaffredo, **OS**, '21]

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?

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



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

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

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

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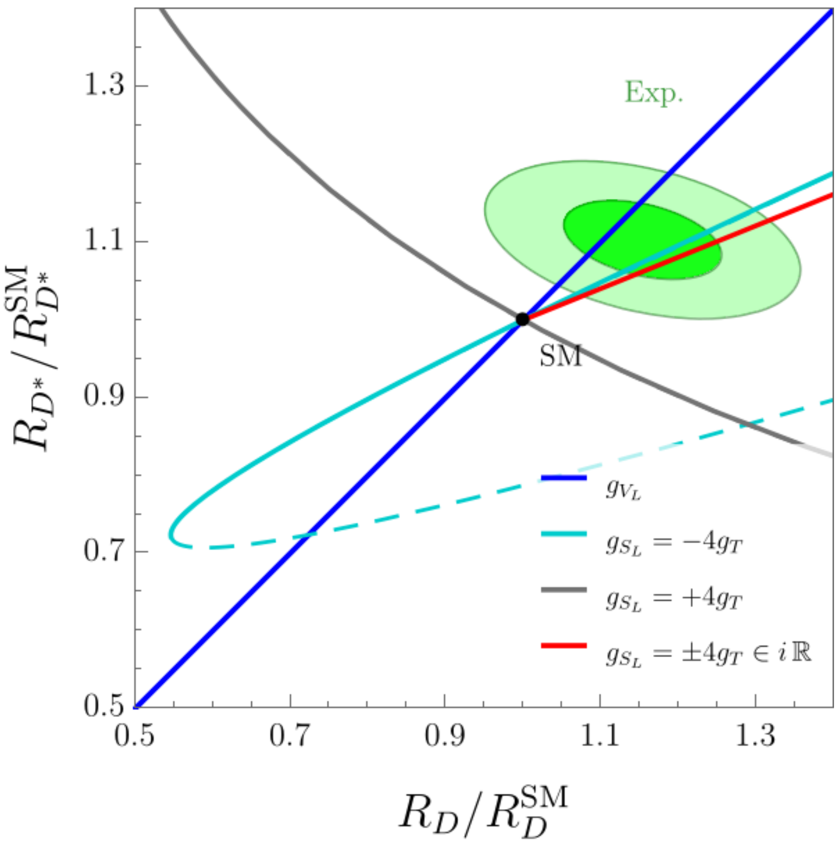
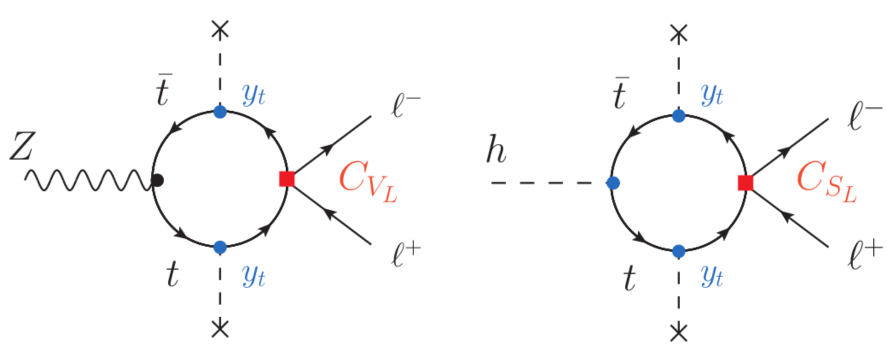




Viable solutions (at $\mu \approx 1$ TeV):

$\Rightarrow$ 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]

From EFT to concrete models

What do we know so far?

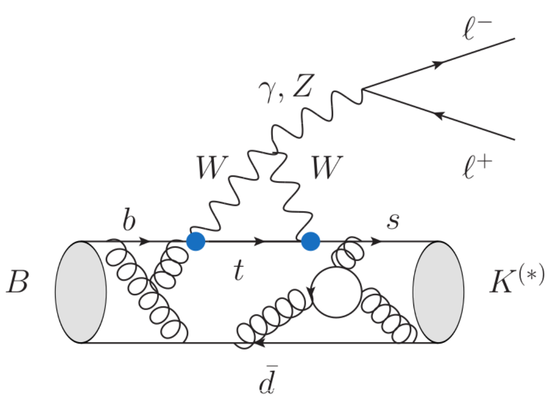
- What is the *scale of New Physics* $(\Lambda_{\rm NP})$?

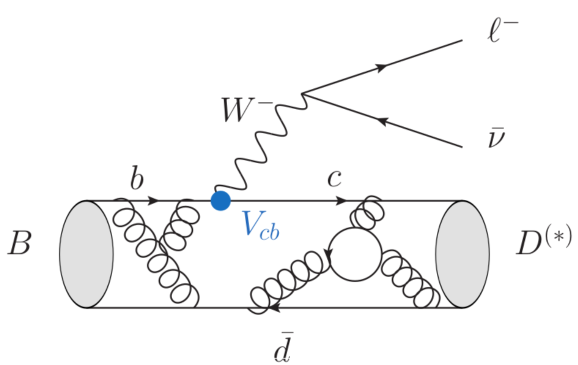
[Di Luzio et al. '17]

$\Rightarrow$ Perturbative couplings:

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

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

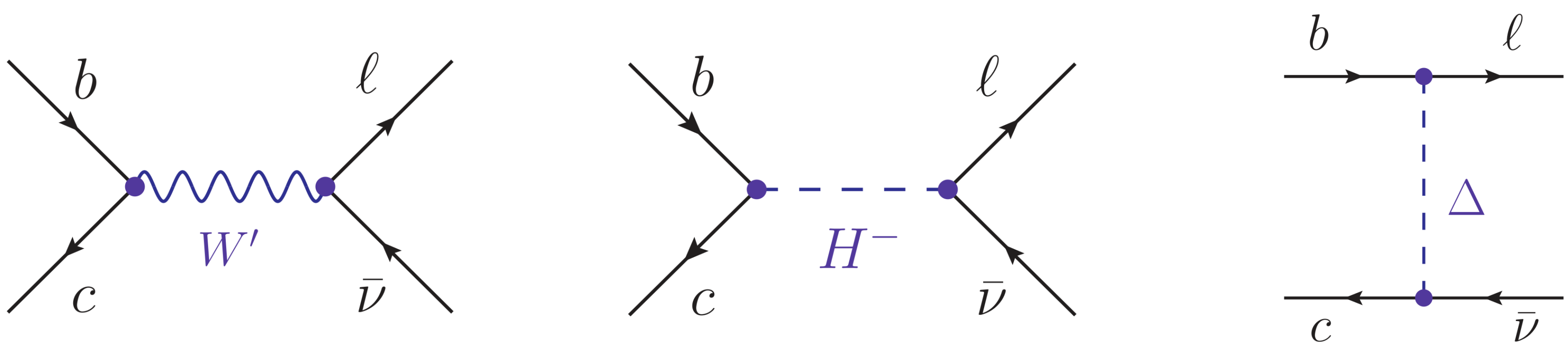




- Moreover, *good agreement* between theory and experiment in *LFU tests with K-, D-* and *τ decays*!

Which mediator?

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



Challenges for concrete scenarios:

- Flavor observables: *e.g.* Δm_{B_s} *and* $B \to K^{(*)}\nu\bar{\nu}$ [Many papers!]
- 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, ...]

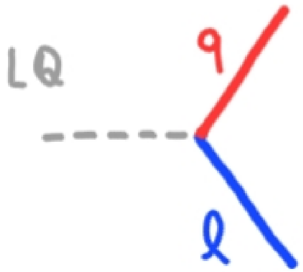
Scalar and vector **leptoquarks (LQ)** are the **best candidates** so far

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?

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

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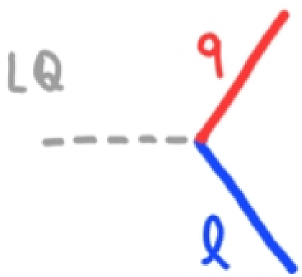


Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_3 $(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	✓	✗	✗
S_1 $(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✗	✓	✗
R_2 $(\mathbf{3}, \mathbf{2}, 7/6)$	✗	✓	✗
U_1 $(\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓
U_3 $(\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗	✗

- Only the U_1 LQ can do the job alone, but UV completion needed.

  $\Rightarrow$ $\mathcal{G}_{\text{PS}} = SU(4) \times SU(2)_L \times SU(2)_R$ 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]

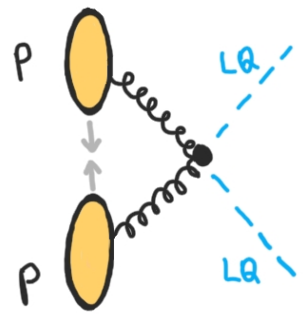
Closing the leptoquark window

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

LHC constraints

i) LQ pair production via QCD:

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



$+ \;\ldots$

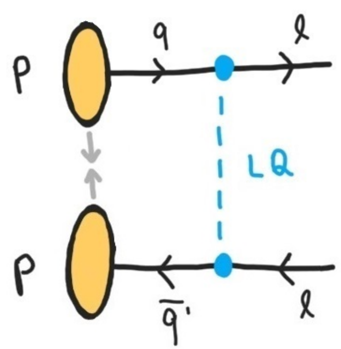
see [Dorsner et al.. '18] for a recent review

[CMS, 2012.04178]

$$m_{U_1} \gtrsim 1.8\ \mathrm{TeV}$$

(assuming dominant couplings to 3rd gen.)

ii) Di-lepton tails at high-p_T:

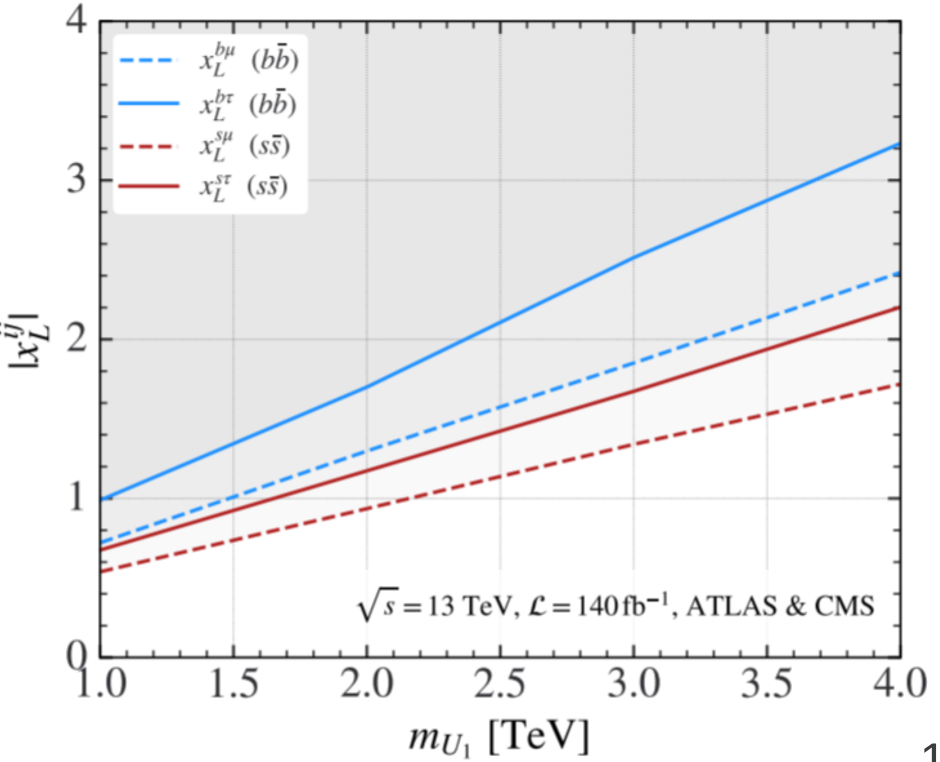


First proposed by [Eboli, '88]

[Faroughy et al. '16]

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

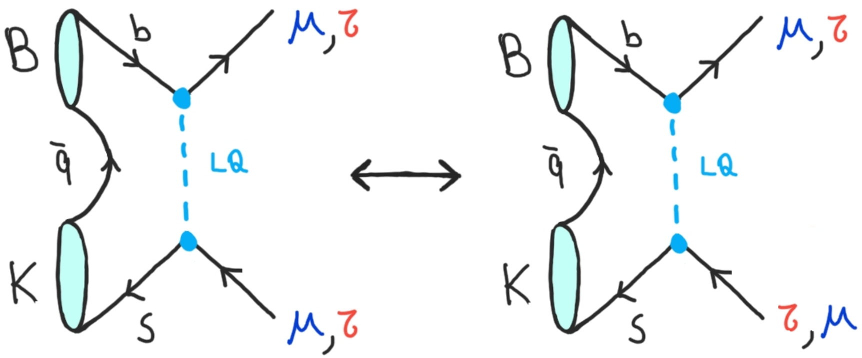
[ATLAS and CMS]



Combining flavor and LHC

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

- **LFU**V ↔ **L**epton **F**lavor **V**iolation



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

[Glashow et al. '14]

Predictions for

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

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

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

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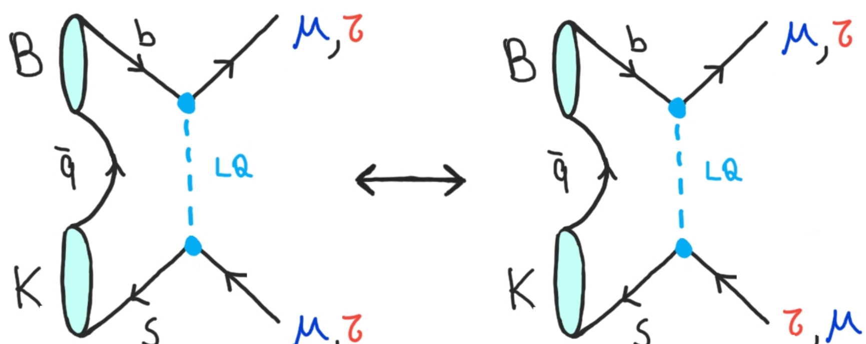

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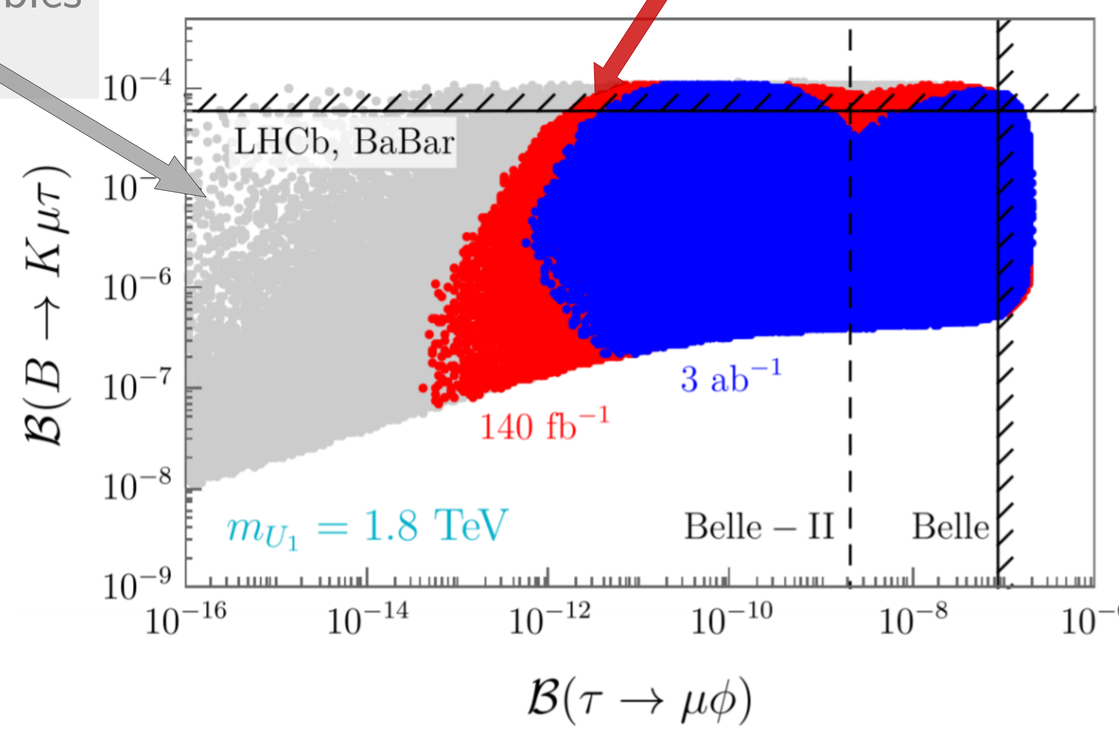
New searches (95% CL):

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

LHC constraints

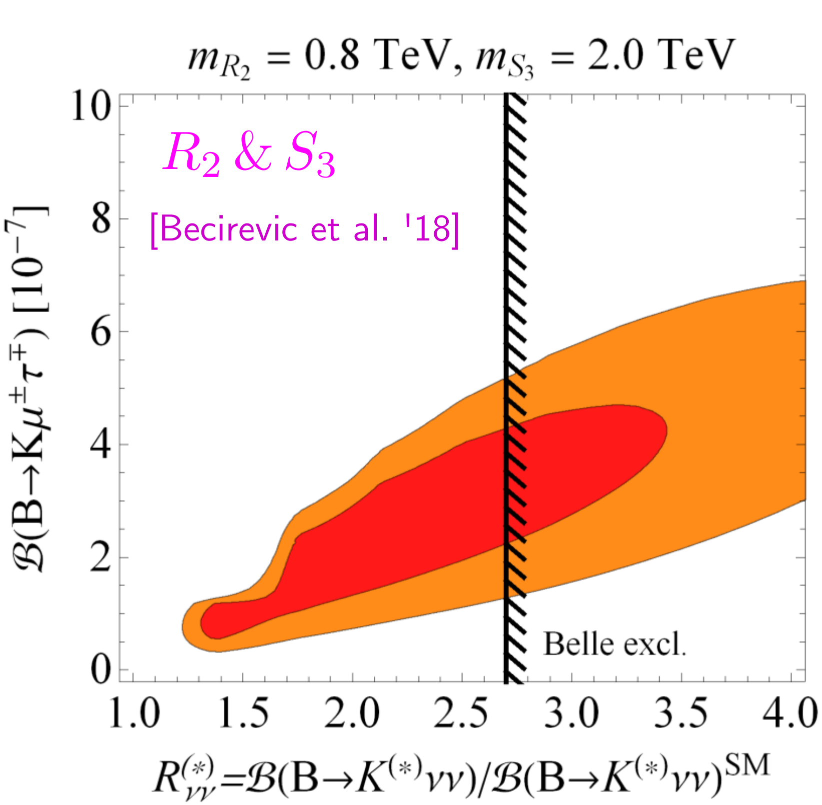
Several flavor observables (at tree-level)

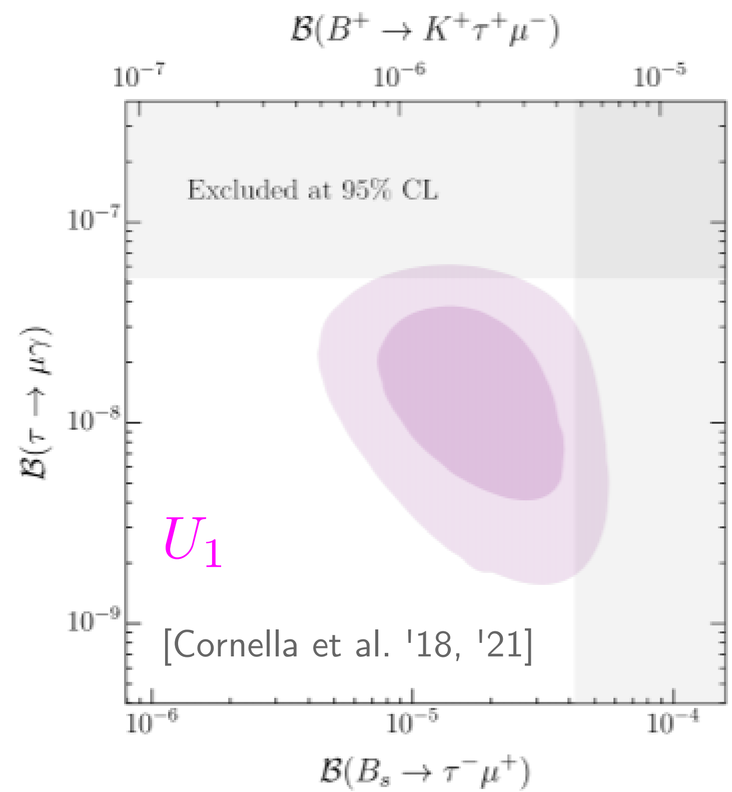


High-p$_T$ constraints set a model-independent **lower bound** on $\mathcal{B}(B \to K\mu\tau)$

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. '16]

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

See talks by Soffer and Watanuki

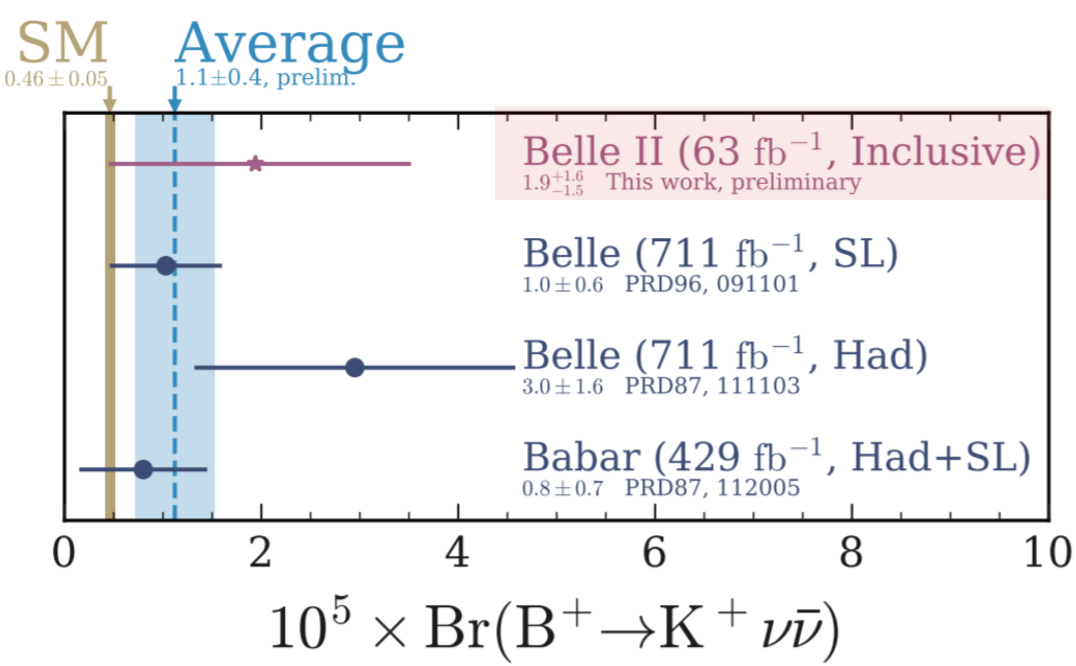
- **Clean observable** in the SM:

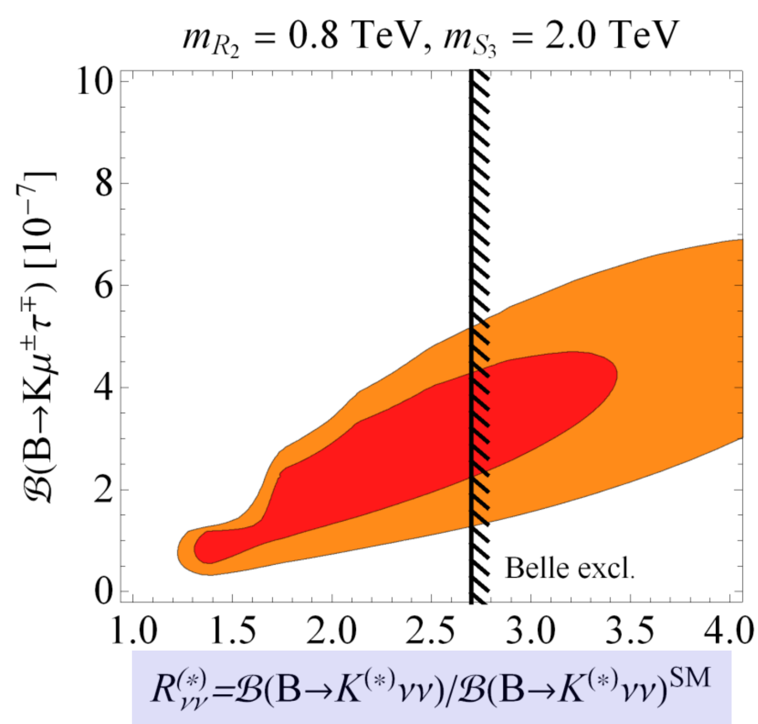
$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})^{\rm SM} = 4.6(5) \times 10^{-6}$$

[Blake et al. 1606.00916]

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

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





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

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

Summary and perspectives

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

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

- We identify the viable single-mediator explanations to $R_{K^{(*)}}$ and/or $R_{D^{(*)}}$.

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

- U_1 model: we 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!

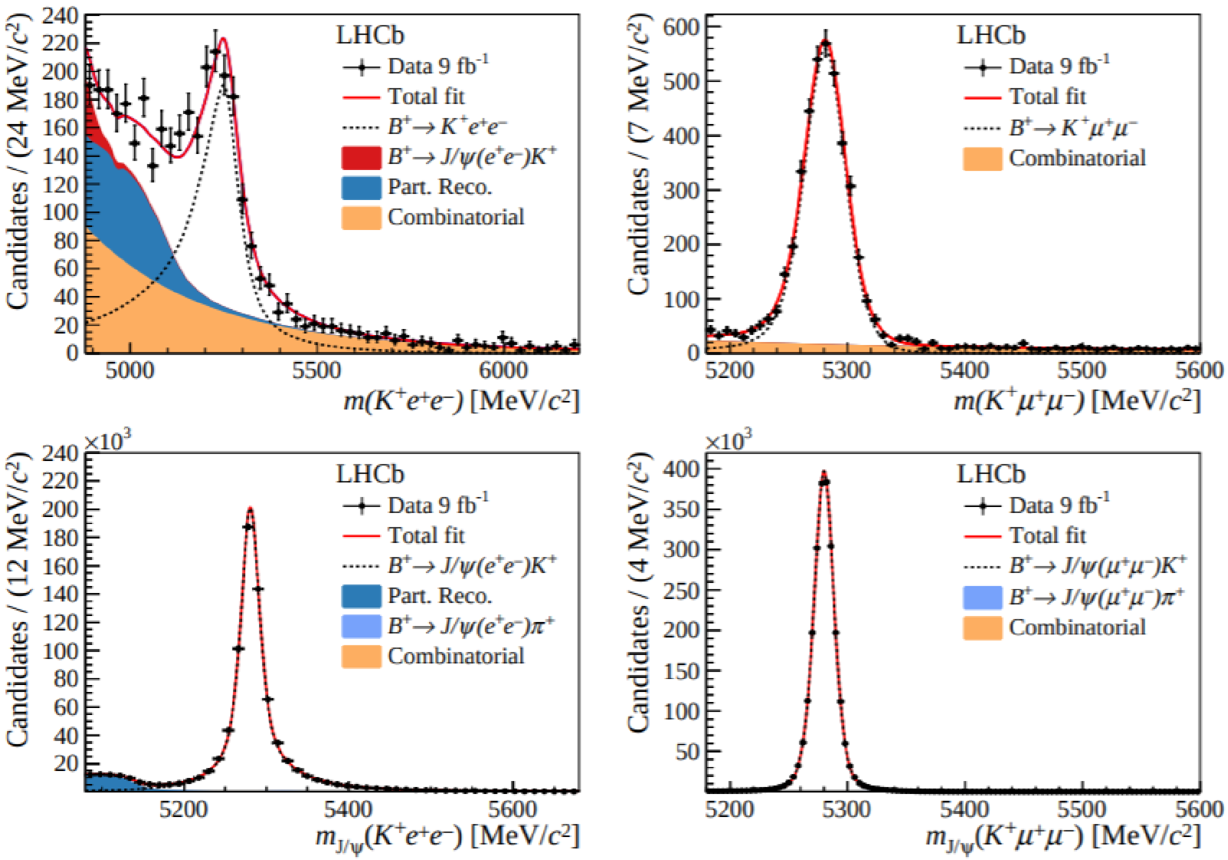
Back-up

Experimental strategy

[LHCb, 2103.11769]

Double ratio

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



Cross-check:

$$r_{J/\psi}^{\text{exp}} = \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))} = 0.98(2)$$

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

Experimental cross-checks

[LHCb, 2103.11769]

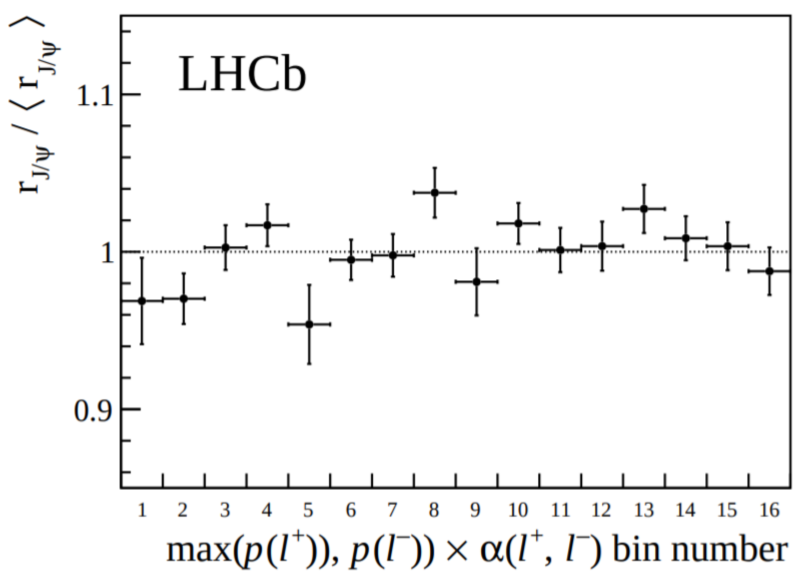
i) LFU at $\psi(2S)$:

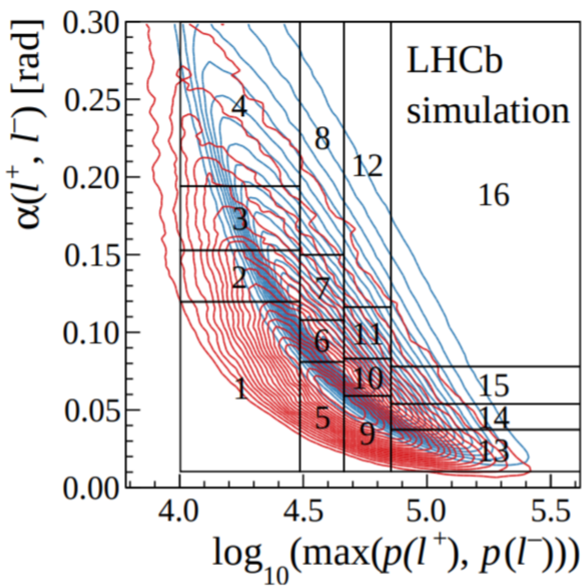
$$R^{\rm exp}_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to K^+ \psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+ \psi(2S)(e^+e^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))}$$

$$= 0.997(11)$$

ii) Dependence on kinematics:

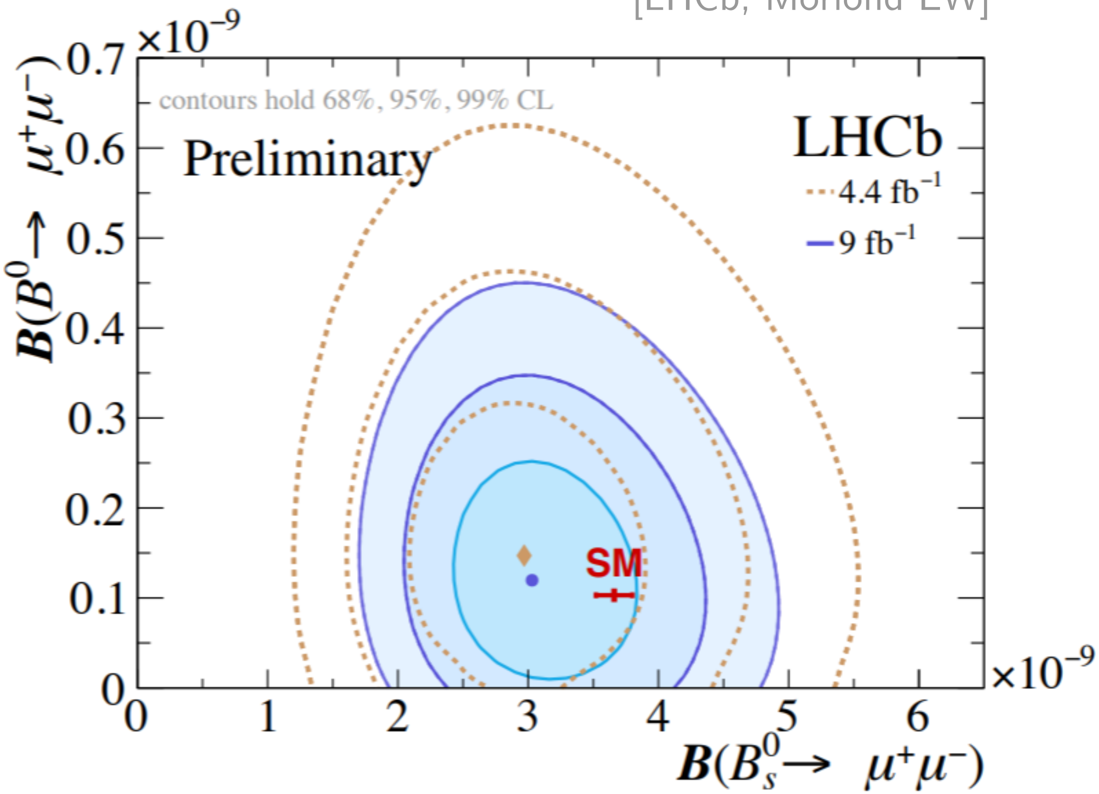
$$r^{\rm exp}_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))}$$



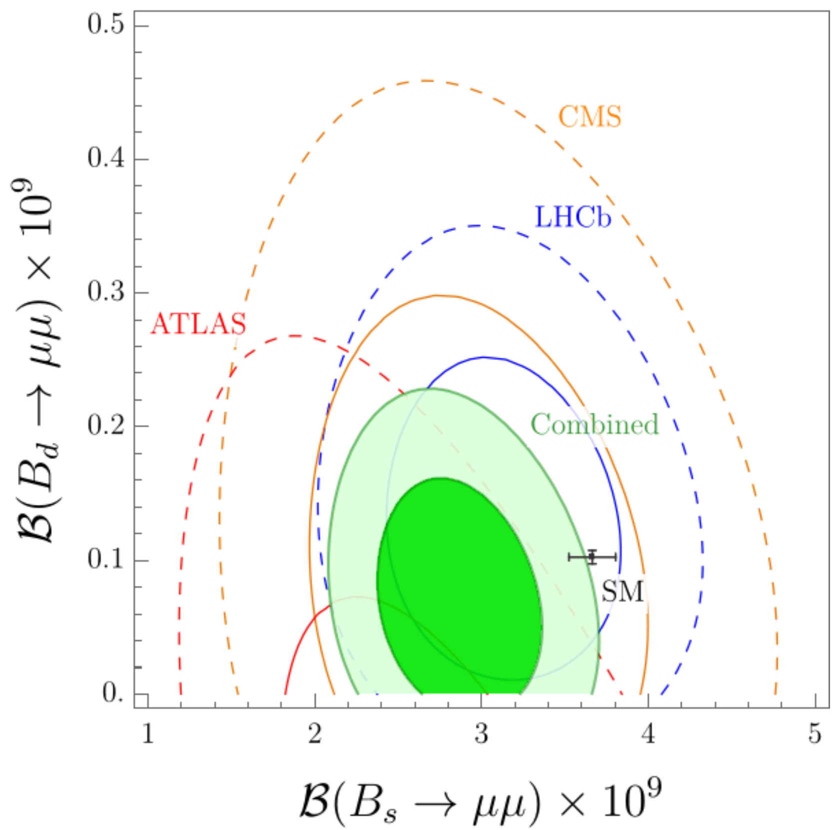


Latest LHCb results

[LHCb, Moriond EW]



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



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

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

[Our average, CMS, ATLAS, LHCb]

[Beneke et al. '19]

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)!

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

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

and assume

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

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

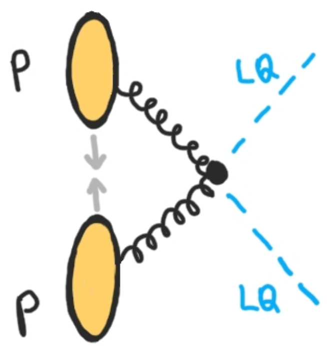
Parameters: m_{R_2}, m_{S_3}, $y_R^{b\tau}$, $y_L^{c\mu}$, $y_L^{c\tau}$ and θ

LHC constraints

LQ pair production

Production dominated by QCD:

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



$+ \ldots$

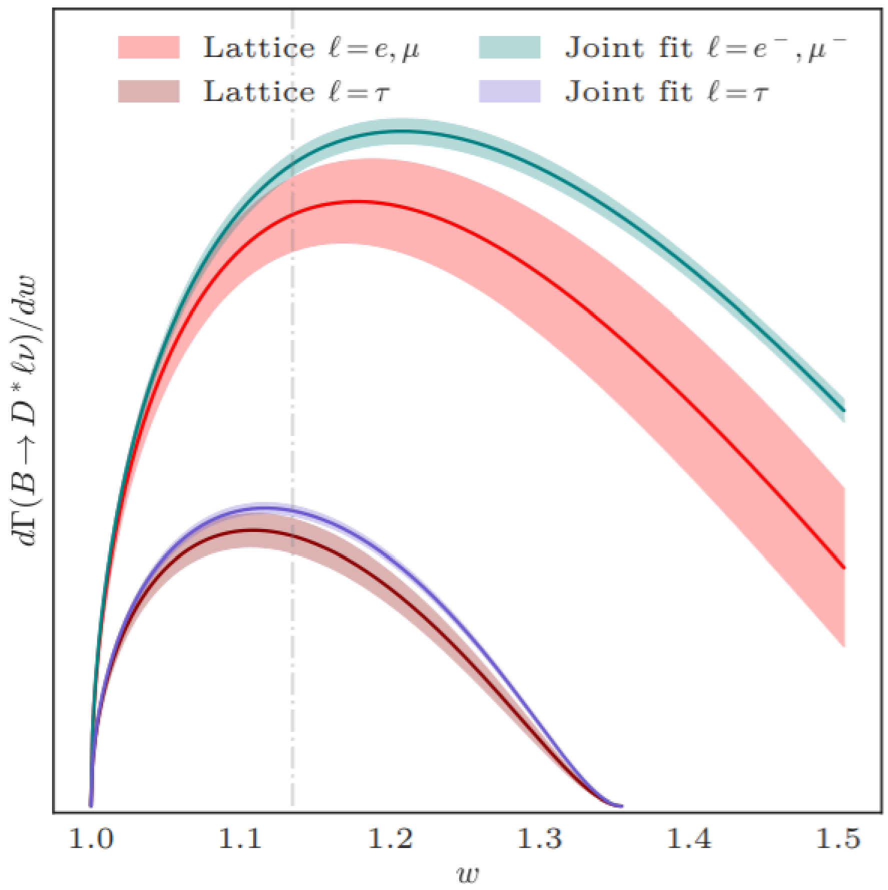
see [Dorsner et al., '18] for a recent review

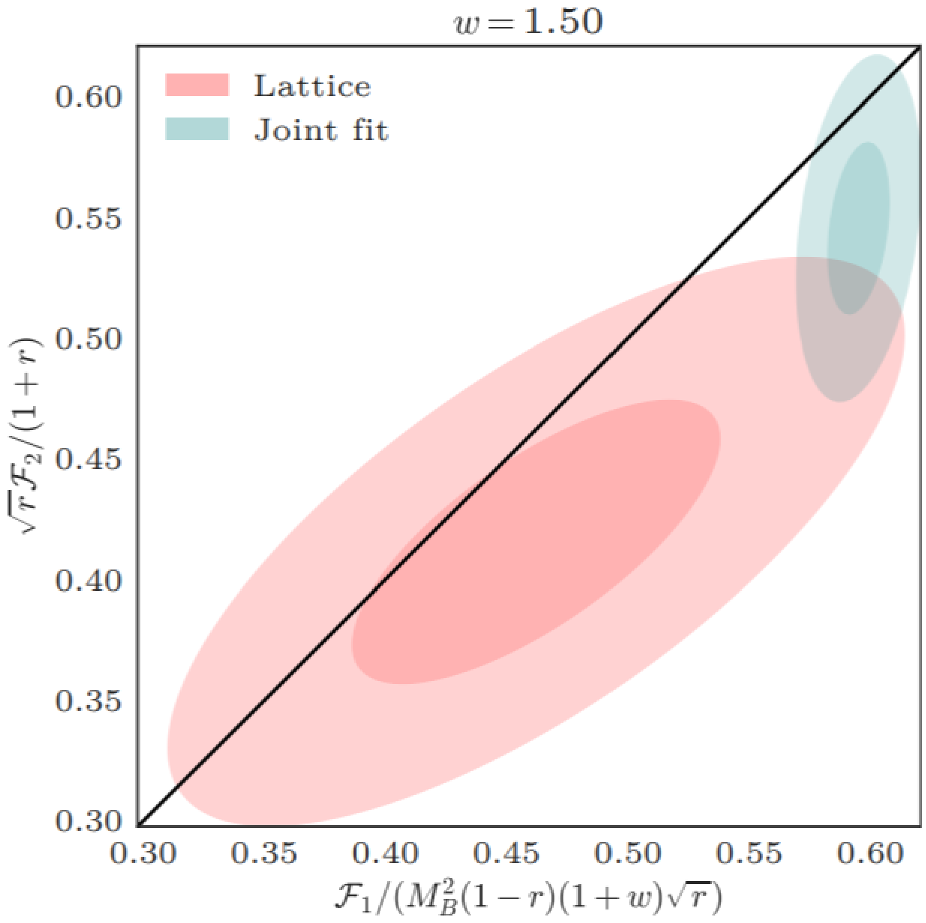
ATLAS and CMS results for $\beta = 1\,(\text{or } 0.5)$

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

[MILC/Fermilab, 2105.14019]





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