Flavor anomalies and their BSM interpretation

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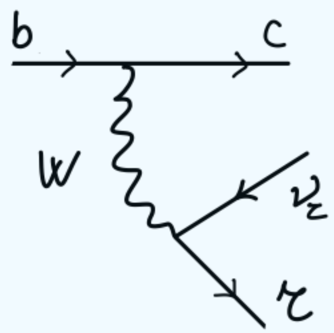
Panic, 5-10.09.2021

The flavor anomalies

$b \to cl\nu$

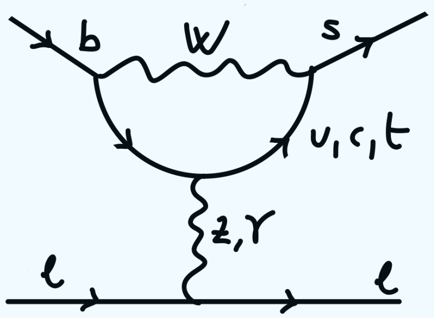
~15% deviation from $\tau/\mu, e$ universality



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

$b \to sll$

~15% deviation from μ/e universality



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

What do we learn from B anomalies?

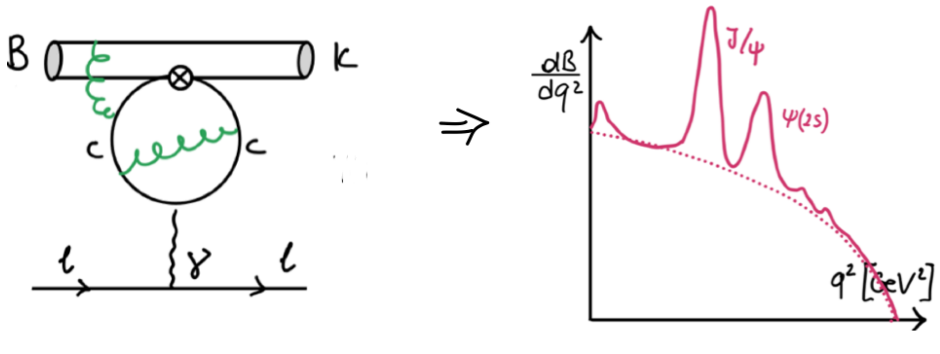
If they are NP signals, where else should we see something?

Data in $b \to sll$

Several discrepancies from the SM in $b \to sll$:

"not-so-clean"

- P_5' ($B \to K^{(*)}\mu\mu$ angular distribution)
- deficit in $\mathscr{B}(B \to X_s\mu\mu)$ $X_s = K, K^*, \phi$



- μ/e LFUV in $B \to K^*ll$, $B \to Kll$
- deficit in $\mathscr{B}(B_s \to \mu\mu)$

"clean"

$$R_{K^{(*)}}^{[1.1,6]\ \mathrm{GeV}^2} = 1.00 \pm 0.01$$

[Bordone et al, 1605.07633]

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

[Beneke et al., 1908.07011]

Recent LHCb updates:

$2.3\,\sigma$ deficit in $B_s \to \mu\mu$ combining ATLAS, CMS, LHCb

$3.1\,\sigma$ in $R_K^{[1.1,6]}$ (*evidence* of LFUV) [LHCb, 2103.11769]

EFT for $b \to sll$

$b \to sll$ data have a simple EFT solution:

$$\mathscr{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{\alpha}{4\pi} \sum_i C_i \mathcal{O}_i$$

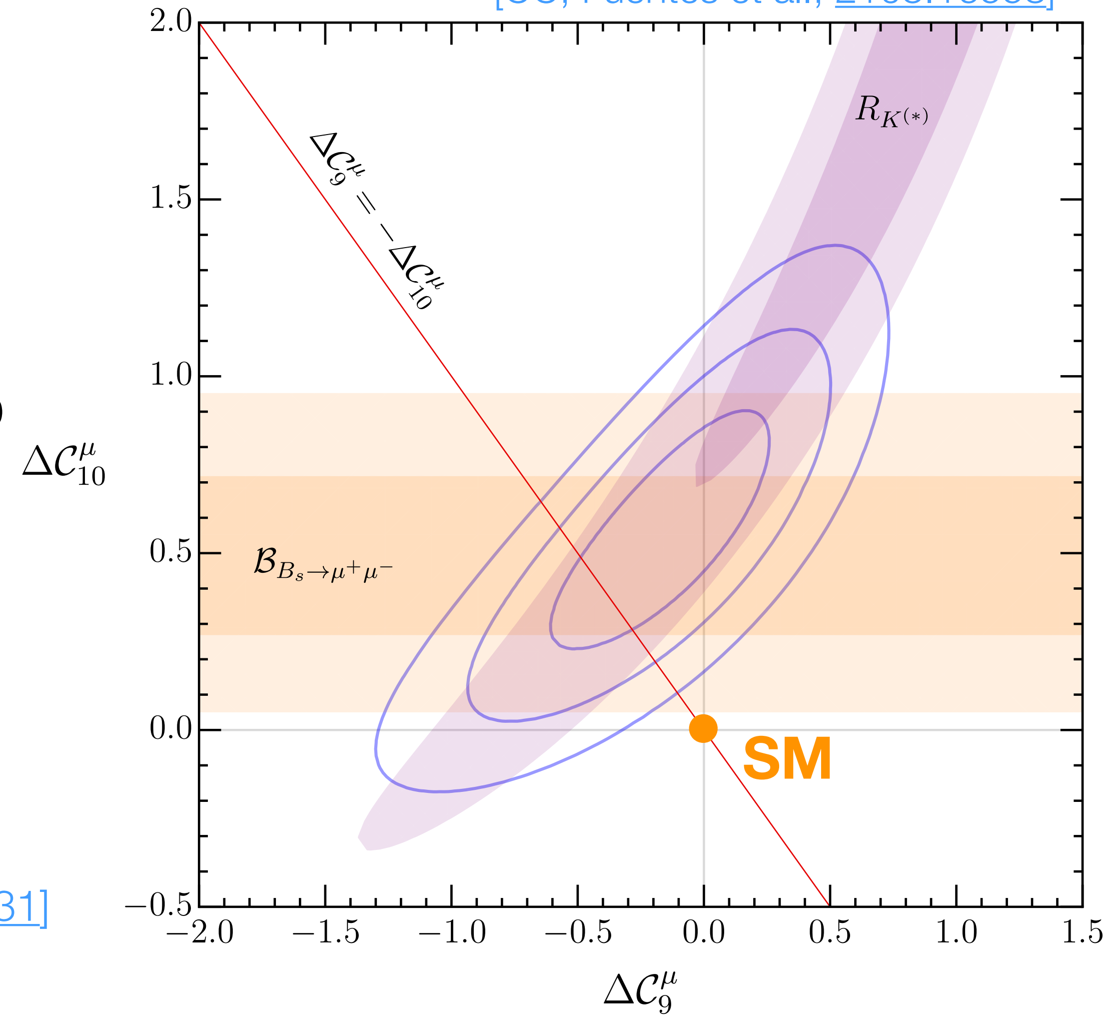
$$\mathcal{O}_9^\mu = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu} \gamma^\mu \mu)$$

$$\mathcal{O}_{10}^\mu = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu} \gamma^\mu \gamma_5 \mu)$$

Fit to **clean observables** only:

left-handed NP hypothesis ($\Delta C_9^\mu = -\Delta C_{10}^\mu$)
preferred by $4.6\,\sigma$ over SM

[CC, Fuentes et al., 2103.16558]



$\sim 4.8\,\sigma$ adding all $b \to sll$ data
(treating ΔC_9^U as nuisance parameter)

$\gg 5\sigma$ with current best estimate of $\bar{c}c$ loop

[Altmannshofer, Stangl, 2103.13370; Algueró et al, 2104.08921; Hurth et al. 2104.10058...]

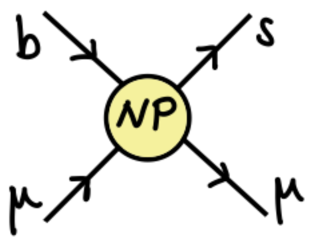
These are ***local* significances** in NP space.

Global? LEE non negligible, still $3.9\,\sigma$

Isidori, Lancierini, Owen, Serra, 2104.05631]

Theory lessons from $b \to sll$

It's a very weak interaction:



$$\sim 3 \times 10^{-5}\ G_F \quad \Rightarrow \quad \frac{g_{\rm NP}^2}{M_{\rm NP}^2} \sim \frac{1}{(40\ {\rm TeV})^2}$$

Direct production could be out of reach, but good chances for indirect discovery:

- build up evidence in $b \to sll$ @LHCb and Belle II
- possibly test LFUV in $b \to dll$

$$R_\pi[q^2_{\rm min}, q^2_{\rm max}] = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \frac{d\mathcal{B}}{dq^2}(B^+ \to \pi^+\mu^+\mu^-)}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \frac{d\mathcal{B}}{dq^2}(B^+ \to \pi^+e^+e^-)} \overset{U(2)}{\approx} R_K^{(*)}$$

clean: pollution from long distance effects < 10% in large q^2 regions

[Bordone, CC, König, Isidori, 2101.11626]

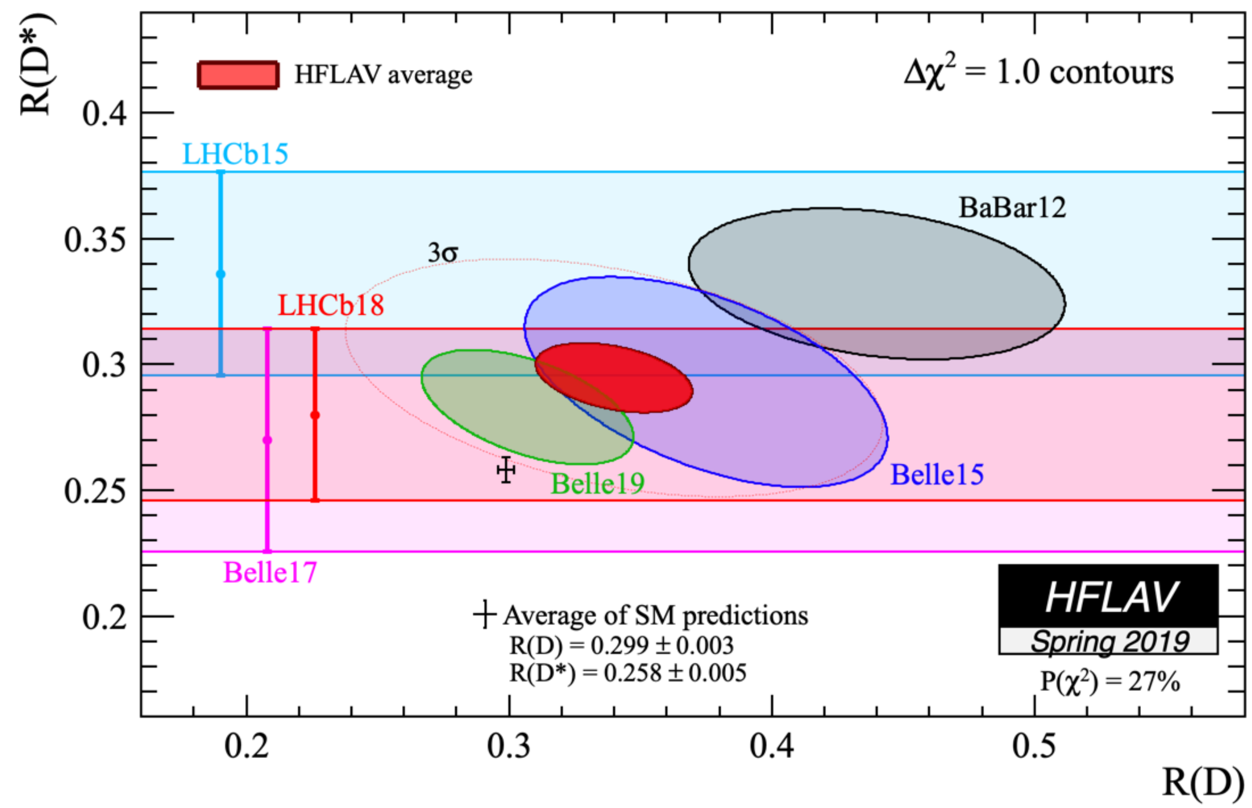
Which models? Z', leptoquarks

Data in $b \to c l \nu$

$$R_{D^{(*)}} \equiv \frac{\mathscr{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathscr{B}(B \to D^{(*)}\ell\bar{\nu})}$$

$\sim 10\,\%$ enhancement of $R_{D^{(*)}}$,
excess seen in tau mode.

[HFLAV]



Also clean SM prediction.
[new: $B \to D^*$ form factors from lattice [Bazavov et al., 2105.14019]]

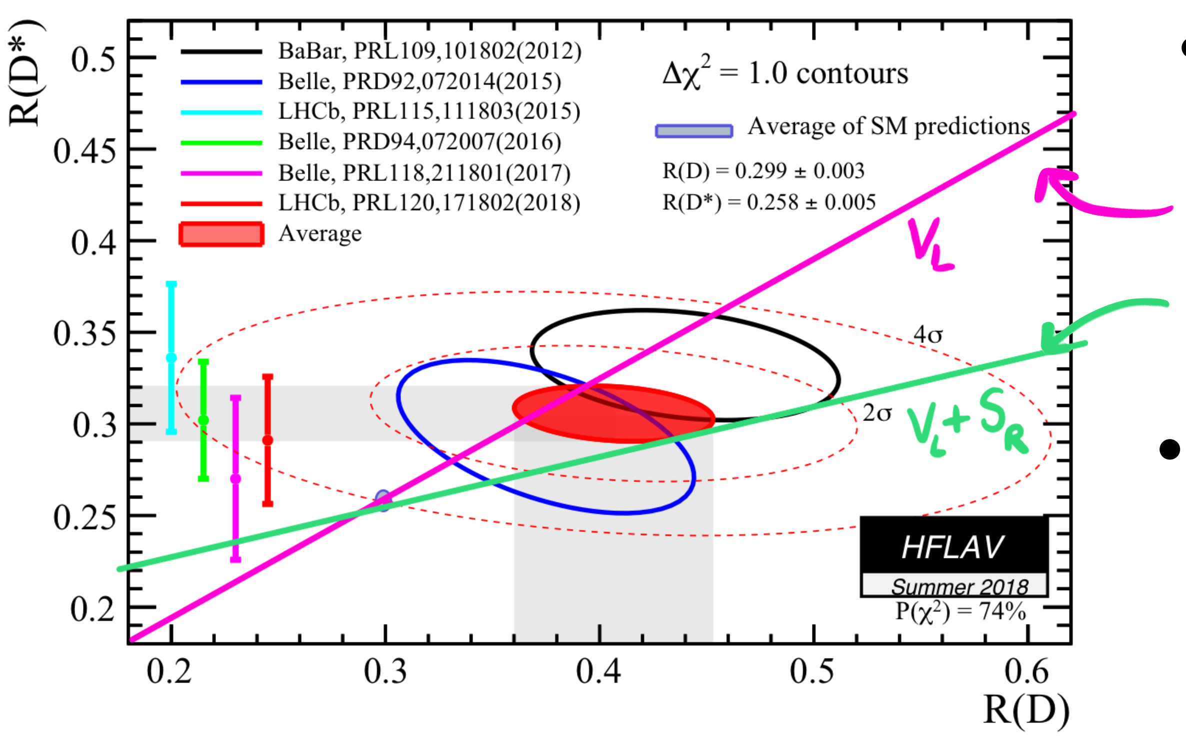
$3.1\,\sigma$ tension combining BaBar, Belle & LHCb results for R_D, R_{D^*}

EFT for $b \to c\tau\nu$

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

Several options: g_{V_L} [Fermi-like interaction] , $g_{V_L}+g_{S_R}$, $g_{S_L}=\pm 4g_T$

Any update in $b \to c\tau\nu$ helps pin down the Lorentz structure:



- NP in LFU ratios:

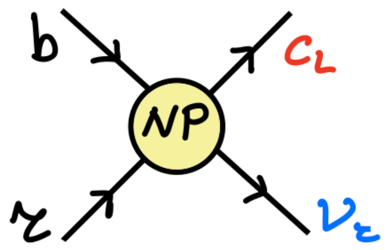
  V_L only $\quad \Delta R_D = \Delta R_D^* \;(= \Delta R_{J/\Psi} = \Delta R_{\Lambda_c})$

  $S, T \neq 0 \quad \Delta R_D \neq \Delta R_{D^*}$

- Angular obs.: largely insensitive to V_L, powerful probe of S, T

Theory lessons from $b \to c\tau\nu$

It's a large effect (competes with *tree level* SM amplitude)



$$\sim 10^{-2}\, G_F \qquad \Rightarrow \quad \frac{g_{\rm NP}^2}{M_{\rm NP}^2} \sim \frac{1}{(2\ \mathrm{TeV})^2}$$

Constraints from low- and high-energy (LFU in τ decays, $pp \to \tau\tau$ tails) make model building for $R_{D^{(*)}}$ challenging

- charged Higgs excluded by τ_{B_c},
- W' in tension with $pp \to \tau\tau$

$\Rightarrow$ **Leptoquarks** (scalar/vector) are the favored candidates.

Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_3 $(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	✓	✗	✗
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[Sumensari et al., 2103.12504

Towards a combined explanation

To account for **both** anomalies:

- $\Lambda_{\mathrm{NP}} \sim$ few TeV
- NP coupled dominantly to 3rd family, smaller couplings to 1st and 2nd
- NP in semileptonic processes only (no 4-lepton/4-quark)

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Minimal SMEFT setup: left-handed NP in semi-leptonic operators

$$\mathscr{L} = -\frac{1}{v^2}\left(C_{\ell q}^{(3)}(\bar{\ell}_L\gamma^\mu\tau^a\ell_L)\left(\bar{q}_L\gamma^\mu\tau^a q_L\right) C_{\ell q}^{(1)}\left(\bar{\ell}_L\gamma^\mu\ell_L)(\bar{q}_L\gamma^\mu q_L\right)\right)$$

works well: ✔ $\Delta C_9^\mu = -\Delta C_{10}^\mu$

✔ V_L solution to $b \to c\tau\nu$

$SU(2)_L \downarrow$

large $b_L \to s_L\tau_L\tau_L$

$\downarrow$

✔ ΔC_9^U by RGE mixing

[Crivellin et al., 1807.02068]

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✓ V_L solution to $b \to c\tau\nu$

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✓ ΔC_9^U by RGE mixing

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! $b \to s\nu_{(\tau)}\bar{\nu}_{(\tau)}$ requires $C_{\ell q}^{(3)} \approx C_{\ell q}^{(1)}$

(automatically satisfied for U_1, needs to be enforced otherwise)

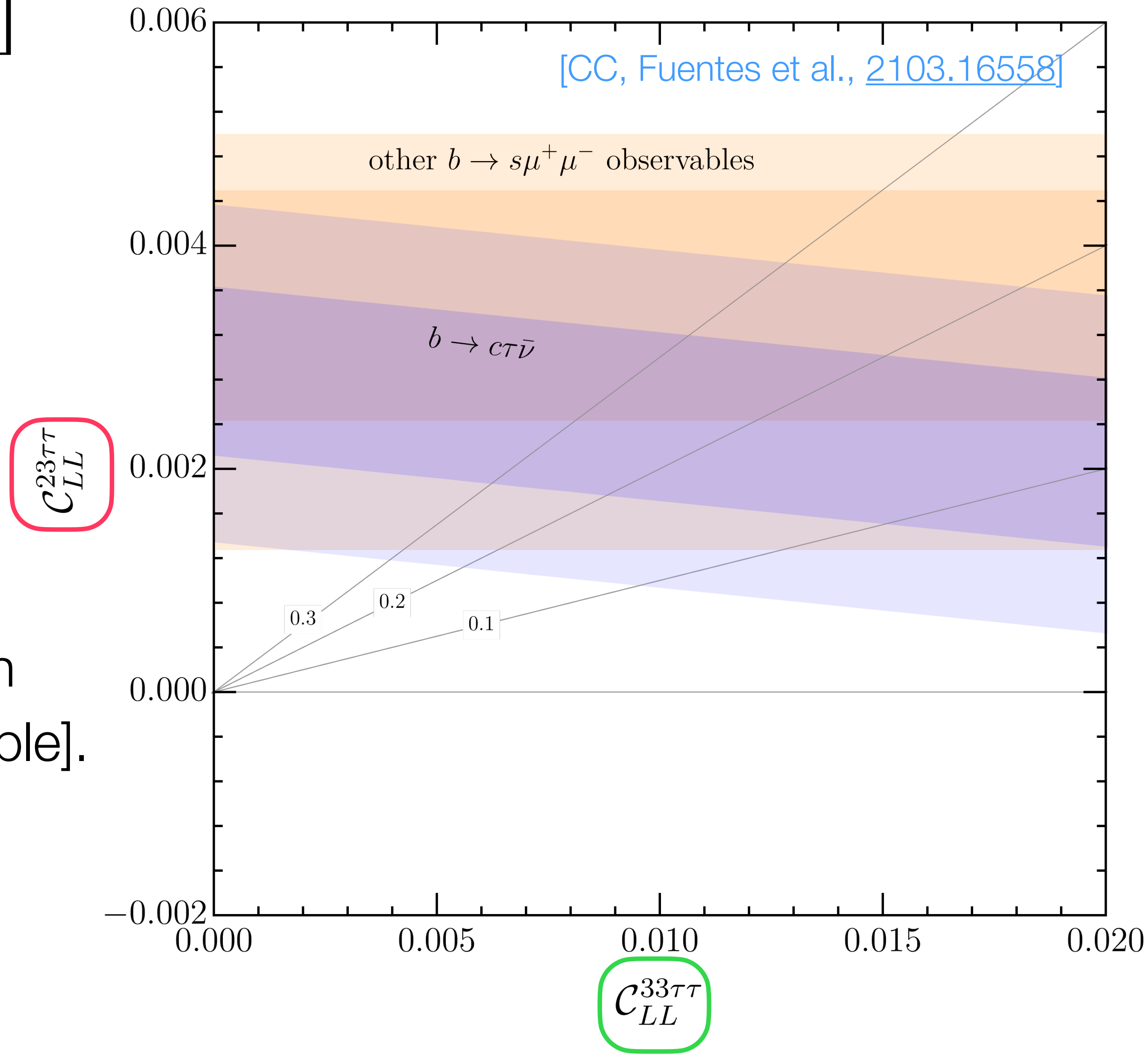
Explaining both sets of anomalies

$$\mathcal{L} = -\frac{2}{v^2} C_{LL}^{ij\alpha\beta} \left(\bar{q}_L^i \gamma^\mu l_L^\alpha\right)\left(\bar{l}_L^\beta \gamma_\mu q_L^j\right)$$

$$R_{D^{(*)}} = R_{D^{(*)}}^{\rm SM} \left[1 + 2{\rm Re}\left(C_{LL}^{33\tau\tau} + \frac{V_{cs}}{V_{cb}} C_{LL}^{23\tau\tau}\right)\right]$$

$$\Delta C_9^\mu = -\Delta C_{10}^\mu \approx -\frac{2\pi}{\alpha V_{ts}^* V_{tb}} C_{LL}^{23\mu\mu}$$

$$\Delta C_9^U \approx \frac{1}{V_{ts}^* V_{tb}} \frac{2}{3} C_{LL}^{23\tau\tau} \ln \frac{\Lambda^2}{m_b^2},$$



Looks like plenty of space to explain $b \to sll$ [orange] and $b \to c\tau\nu$ [purple].

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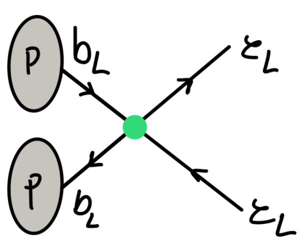
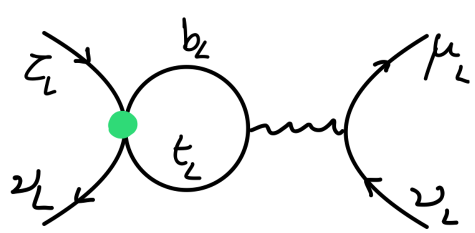
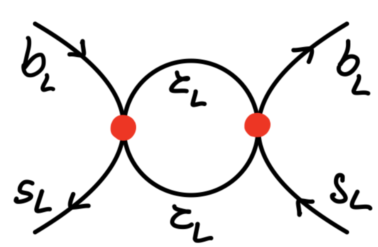
Many other constraints:



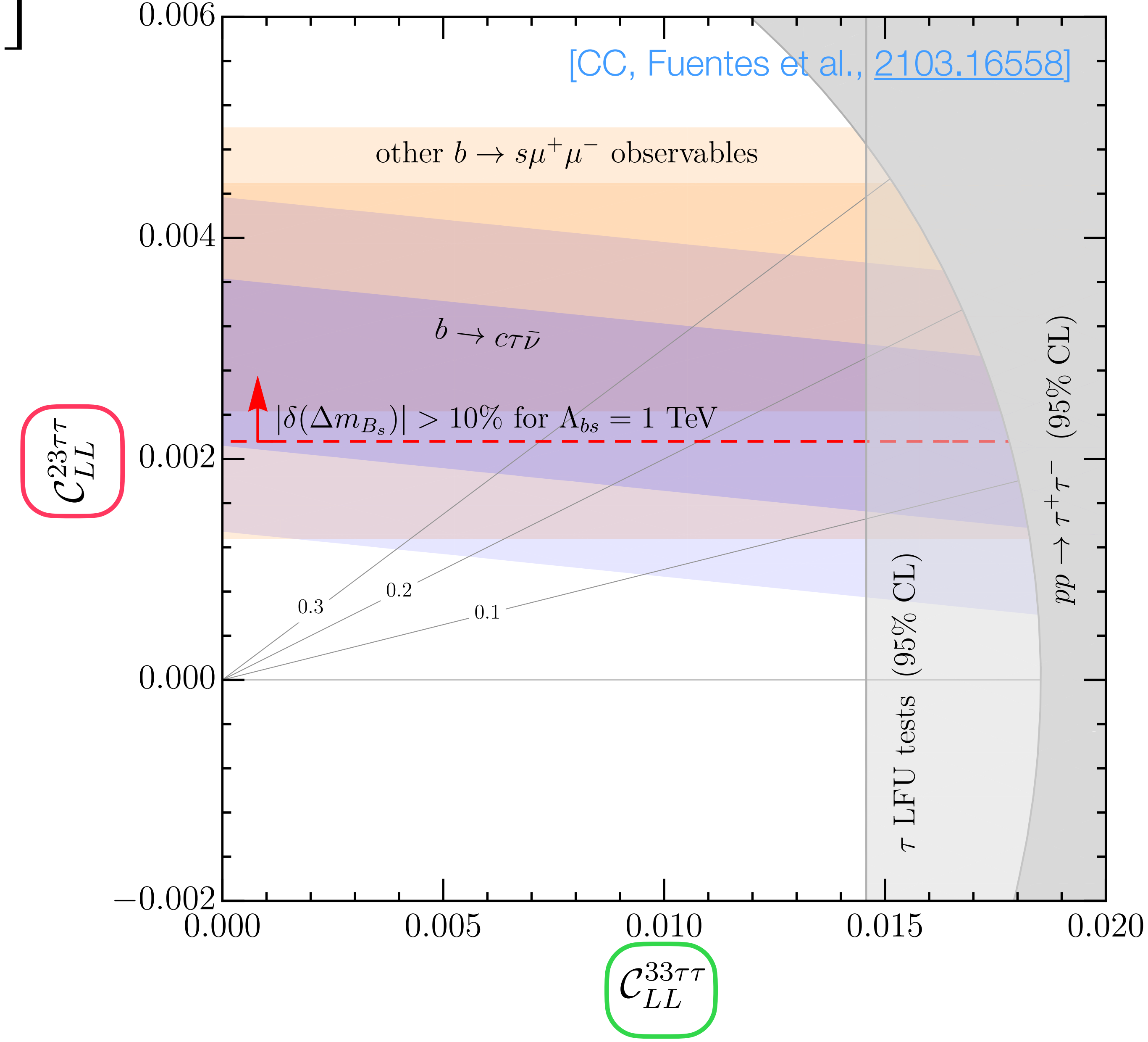
$pp \to \tau\tau$



τ LFU tests



$B_s - \bar{B}_s$



…not much wiggle room!

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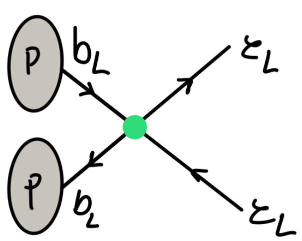

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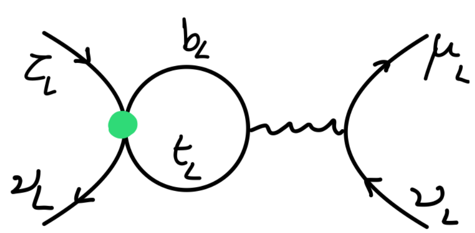

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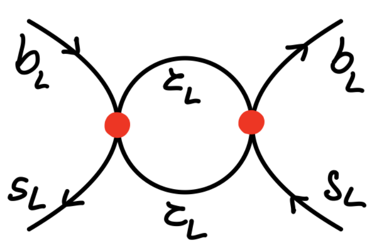

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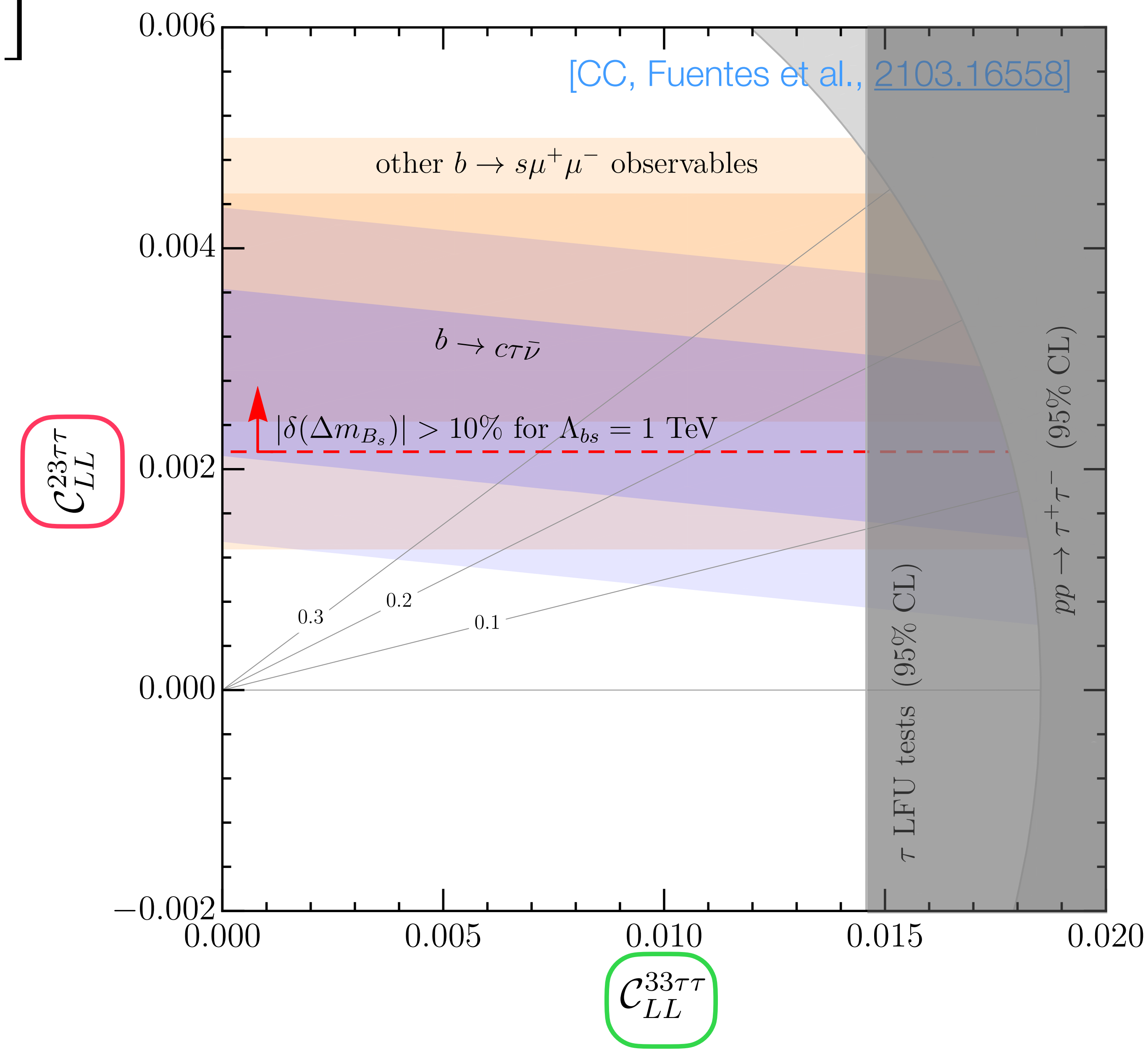

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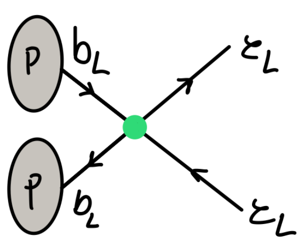

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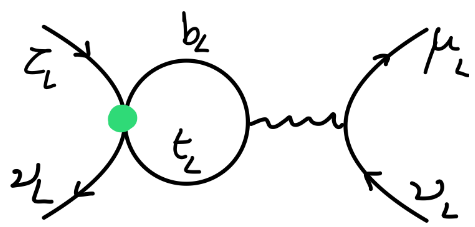

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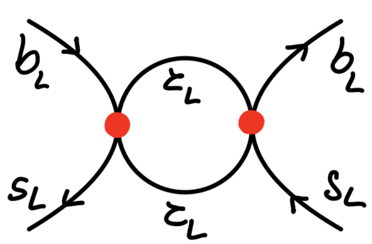

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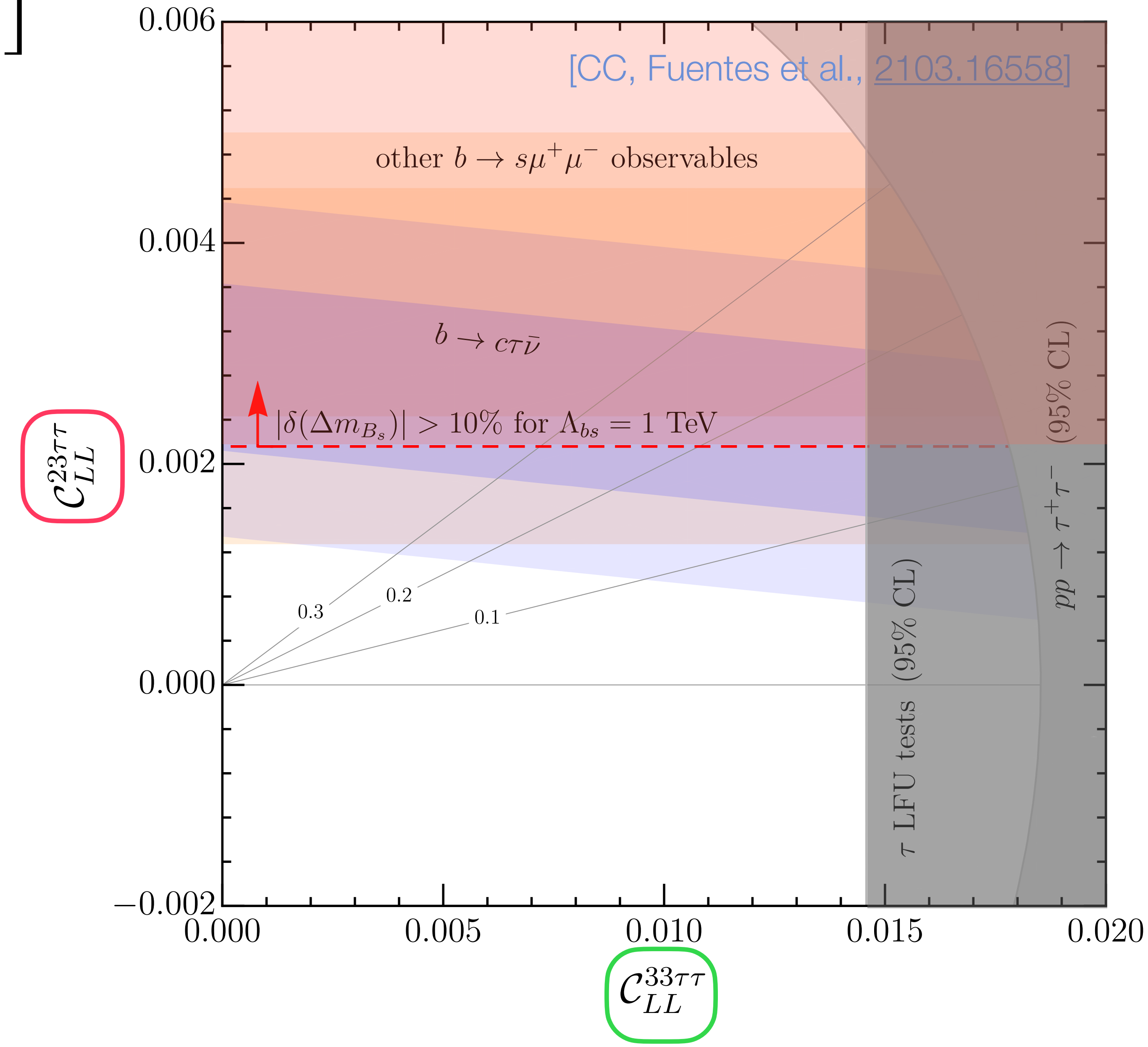
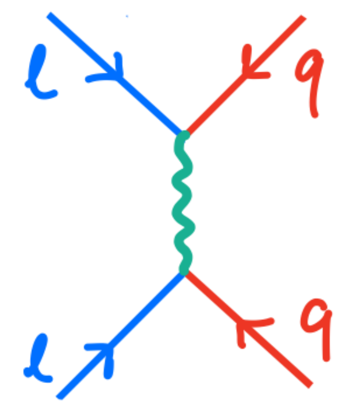


Simplified models for B anomalies: leptoquarks.

The only viable mediators are **leptoquarks**:

- no 4-lepton and 4-quark at tree level,
- no resonant production at high-p_T



Which LQ explains what?

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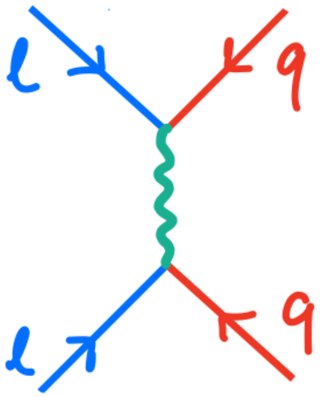

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Three possibilities for both anomalies:

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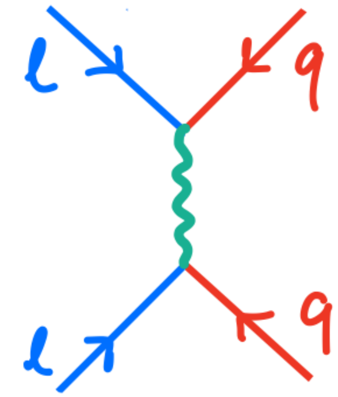

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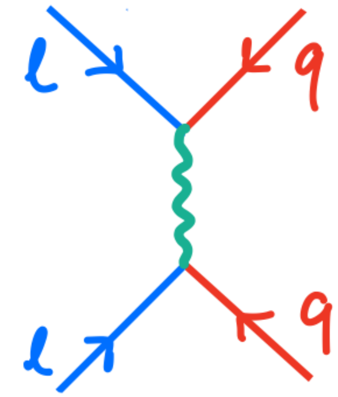

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$S_3 + R_2$ [Bečirević et al., 1806.05689]

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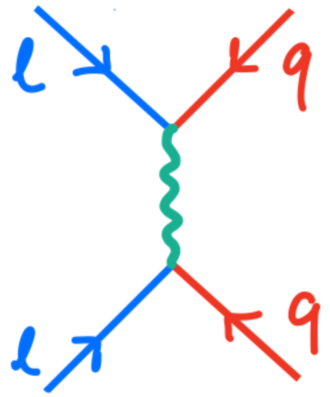

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$U_1 \sim (3, 1)_{2/3}$ (+ UV completion)

[di Luzio et al., 1708.08450; Calibbi et al., 1709.00692; Bordone, CC, et al. 1712.01368; Barbieri, Tesi 1712.06844; Heck,Teresi 1808.07492…]

The U_1 simplified model

The **vector leptoquark** is the only single mediator solution:

- ✓ no tree-level contribution to $b \to s\nu\bar{\nu}$,   protected from proton decay
- ! does not come alone: additional massive vectors (Z', G'), vector-like fermions

The U_1 simplified model

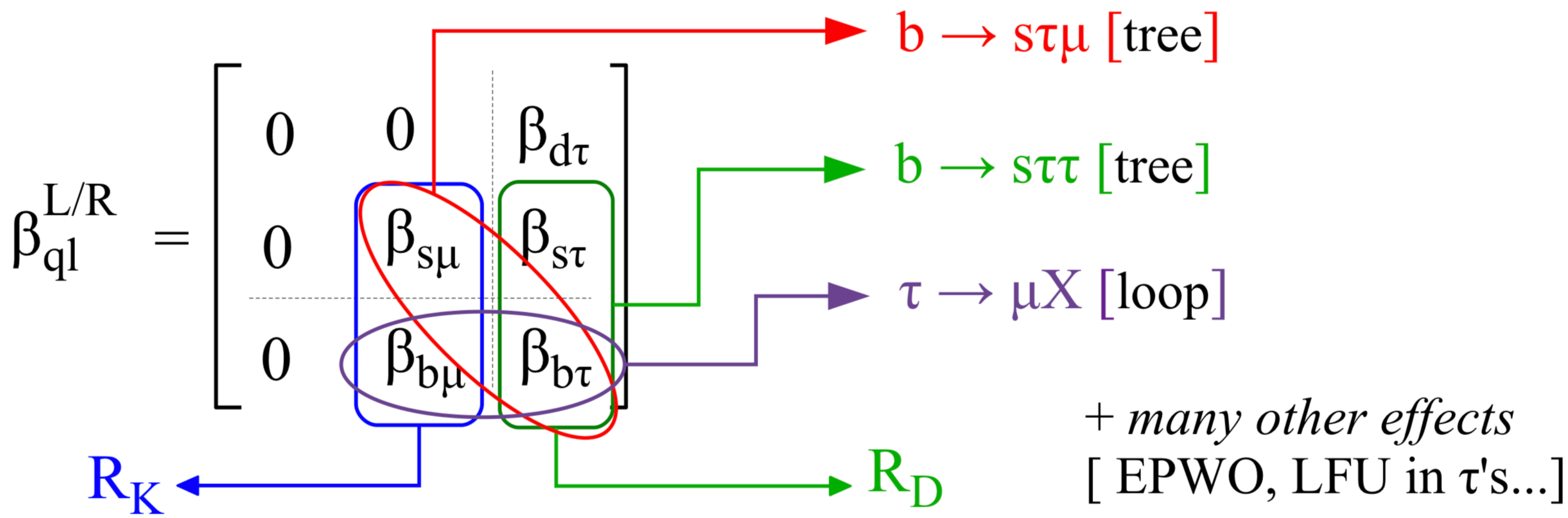
The **vector leptoquark** is the only single mediator solution:

- ✓ no tree-level contribution to $b \to s\nu\bar{\nu}$, protected from proton decay
- ! does not come alone: additional massive vectors (Z', G'), vector-like fermions

Stick to simplified model:

$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta_L^{i\alpha} (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) + \beta_R^{i\alpha} (\bar{d}_R^i \gamma_\mu e_R^\alpha)\right] + \mathrm{h.c.} \qquad U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$$

Good description of all low-energy data with a “natural” flavor structure:



$\beta_{b\tau}^L = 1$

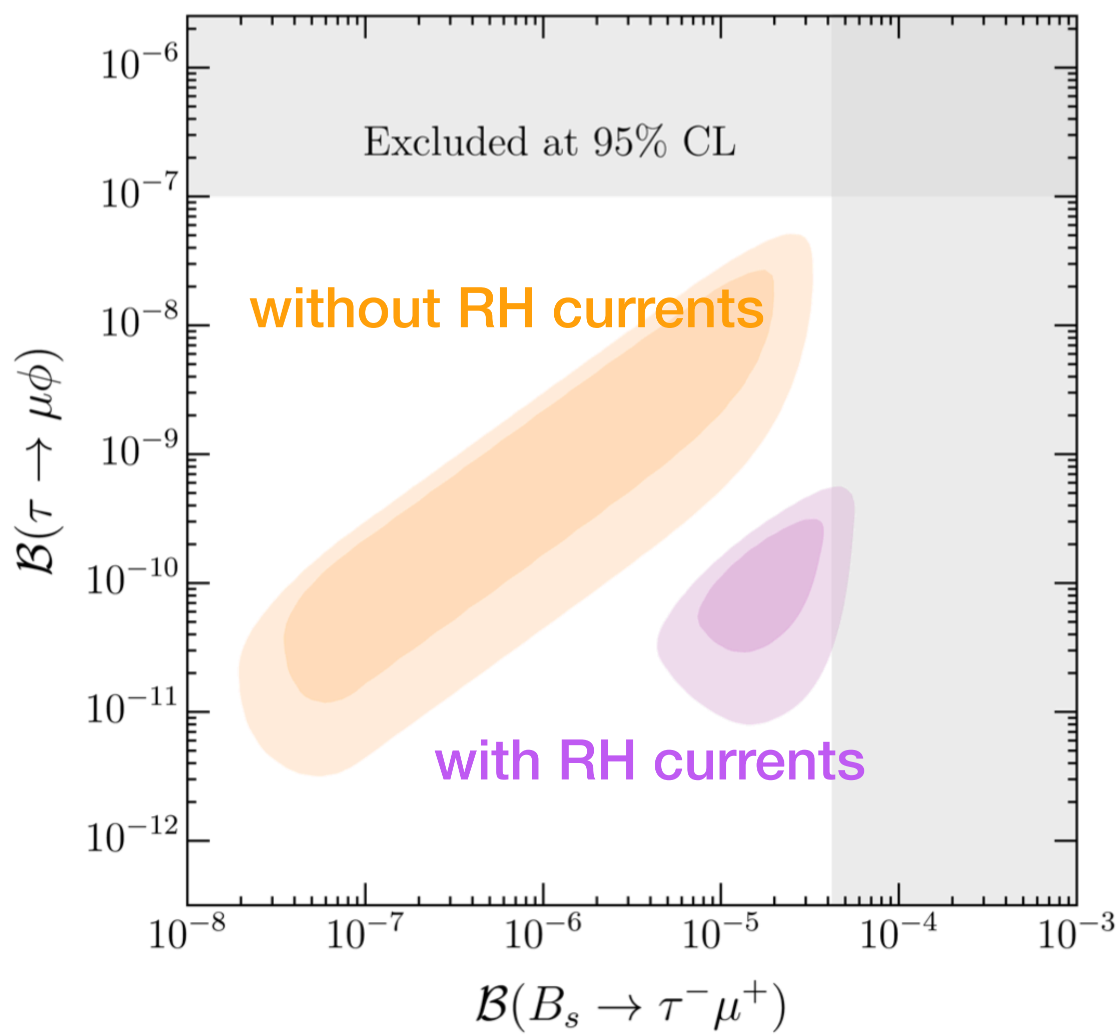
$\beta_{b\tau}^R \sim \mathcal{O}(1)$

$\beta_{s\tau}^L, \beta_{b\mu}^L \sim \mathcal{O}(0.1)$

$\beta_{s\mu}^L, \beta_{d\tau}^L \sim \mathcal{O}(0.01)$

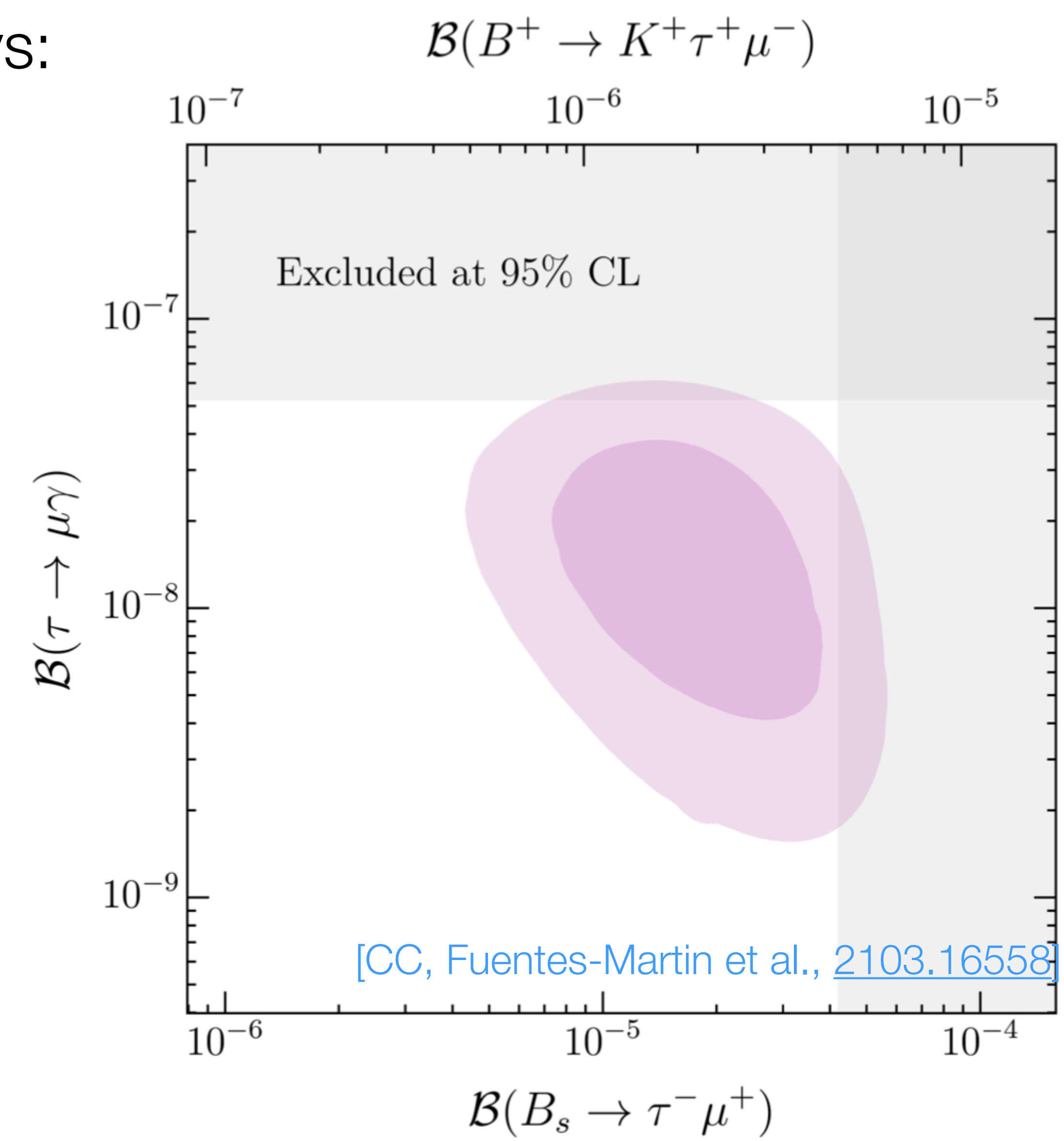
Low-energy predictions for the U_1

Large τ/μ LFV in $b \to s\tau\mu$ and τ decays:



$$\mathcal{B}(B_s \to \tau\mu) \approx \mathcal{B}(B \to K\tau\mu) \approx 10^{-7} - 10^{-6}$$

$$\mathcal{B}(\tau \to \mu\phi) \approx 10^{-10} - 10^{-8}$$



[CC, Fuentes-Martin et al., 2103.16558]

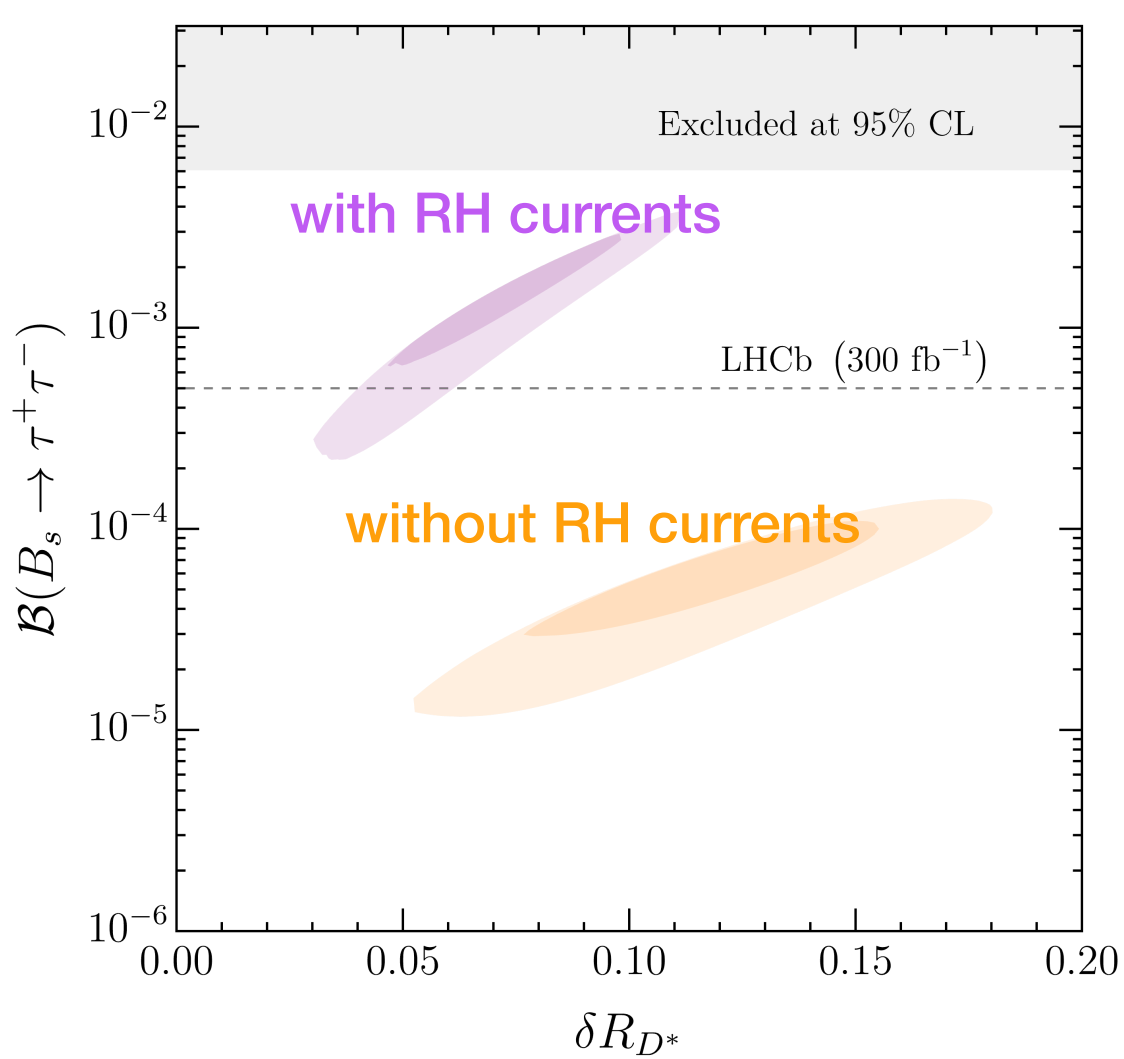
$$\mathcal{B}(B_s \to \tau\mu) \approx 1 \times 10^{-5}$$

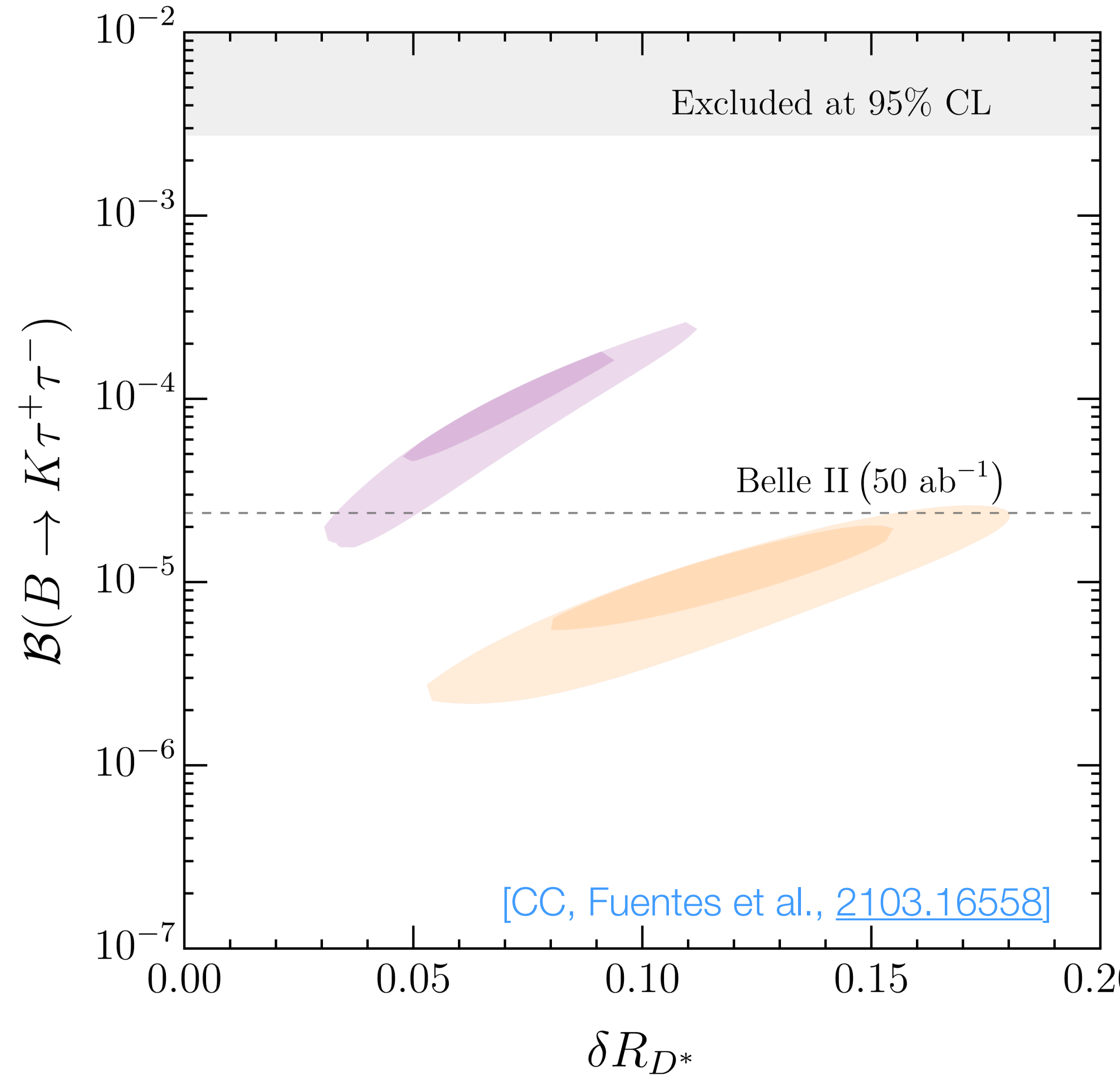
$$\mathcal{B}(B \to K\tau\mu) \approx 1 \times 10^{-6}$$

$$\mathcal{B}(\tau \to \mu\gamma) \approx 1 \times 10^{-8}$$

Low-energy predictions for the U_1

Large $b \to s\tau\tau$:





$$\frac{\mathcal{B}(B_s \to \tau\tau)}{\mathcal{B}(B_s \to \tau\tau)_{\rm SM}} \approx \frac{\mathcal{B}(B \to K\tau\tau)}{\mathcal{B}(B \to K\tau\tau)_{\rm SM}} \approx 1 \times 10^2$$

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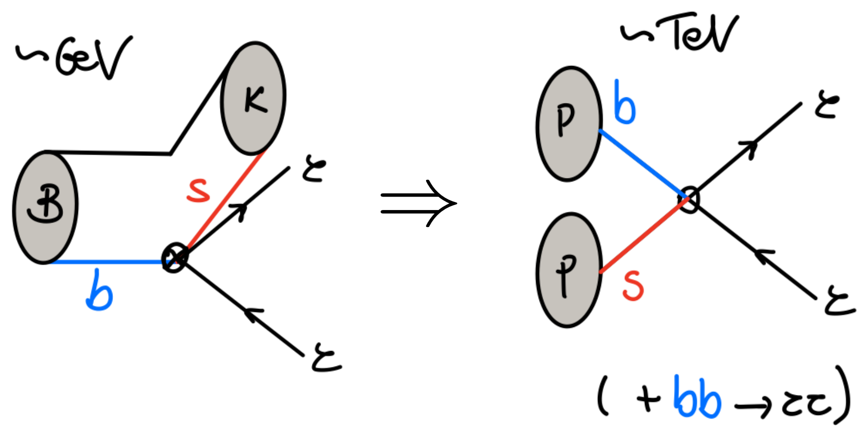
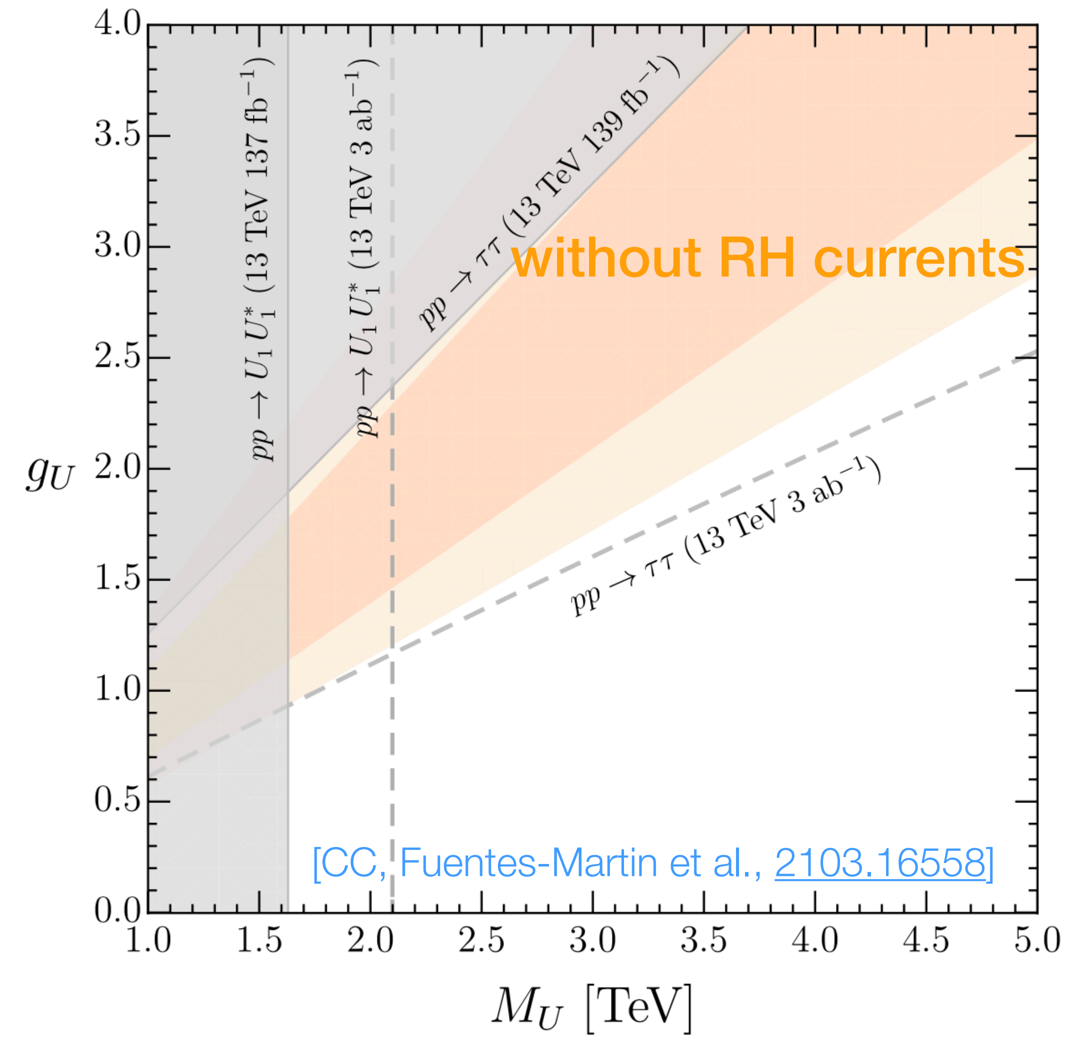
High-pT bounds for the U_1

The same interaction can be probed in **di-tau tails.**

[Faroughy et al, 1609.07138; Fuentes-Martin et al. 2003.12421..]





U_1 solution completely falsifiable at HL-LHC!
(same for $R_2 + S_3$, still space left for $S_1 + S_3$)

Similar enhancements in all models for $R_D^{(*)}$.

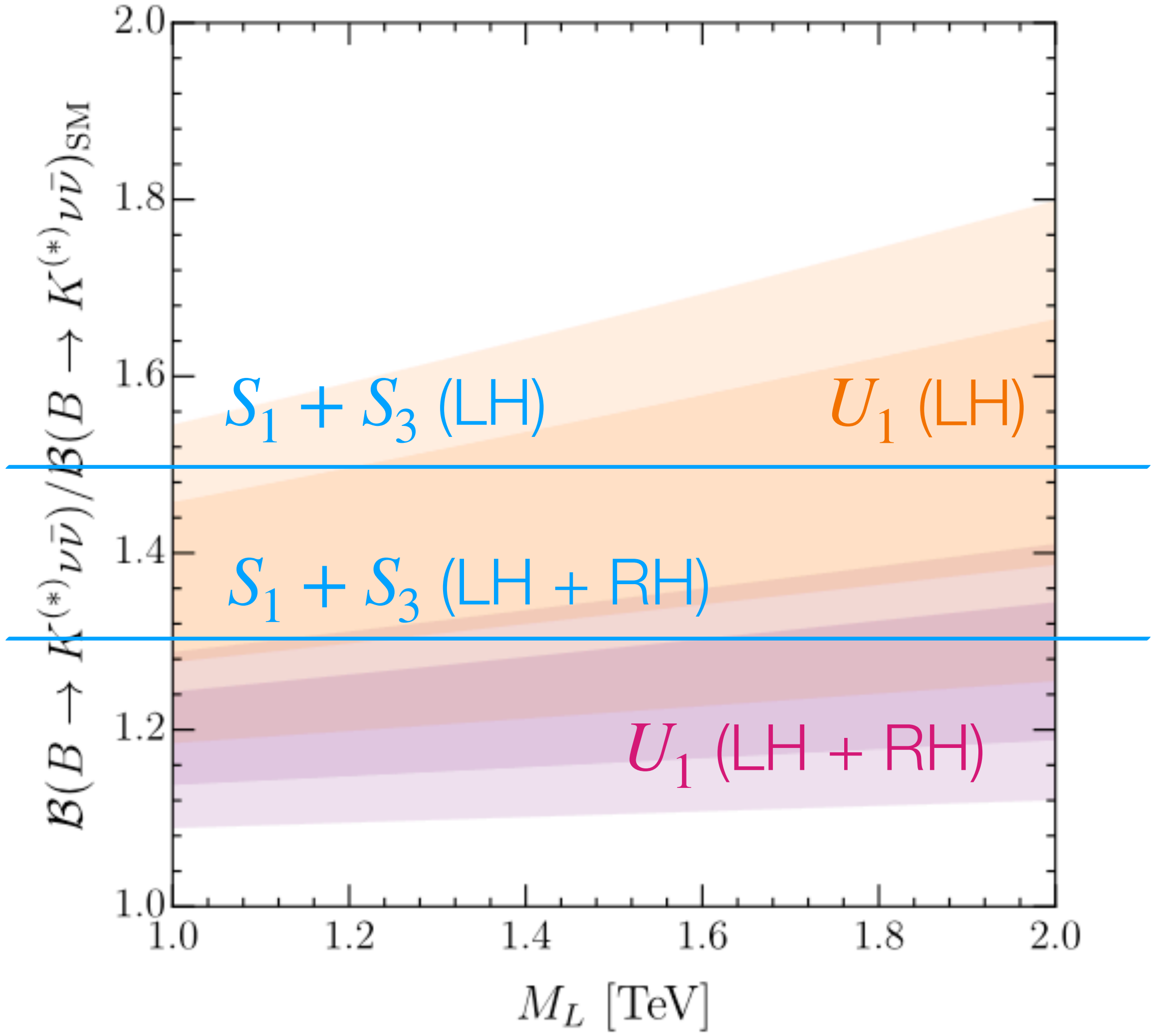
Caveat: these conclusions are *very* sensitive to the central value of $R_D^{(*)}$!

$B \to K\nu\bar{\nu}$ and B anomalies

One of the toughest constraints for model building; all combined solutions enhance it.

$U_1, S_1 + S_3$ $$\frac{\mathcal{B}(B \to K\nu\nu)}{\mathcal{B}(B \to K\nu\nu)_{\rm SM}} \approx 1.2 - 1.5$$

- for the U_1 absent at tree level, but any UV completion generates it at one loop
- $S_1 + S_3$ tuned to cancel interference with SM



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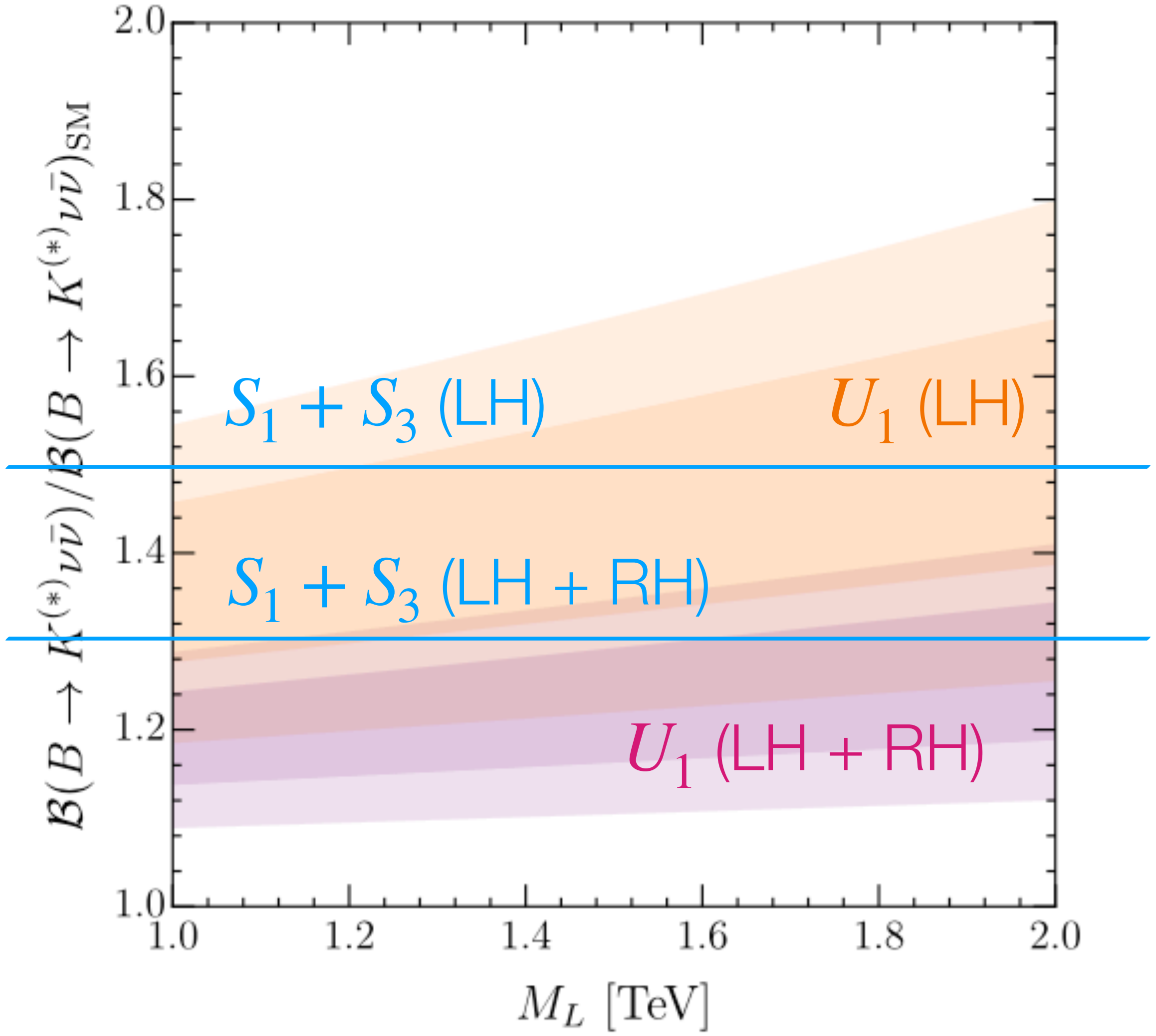

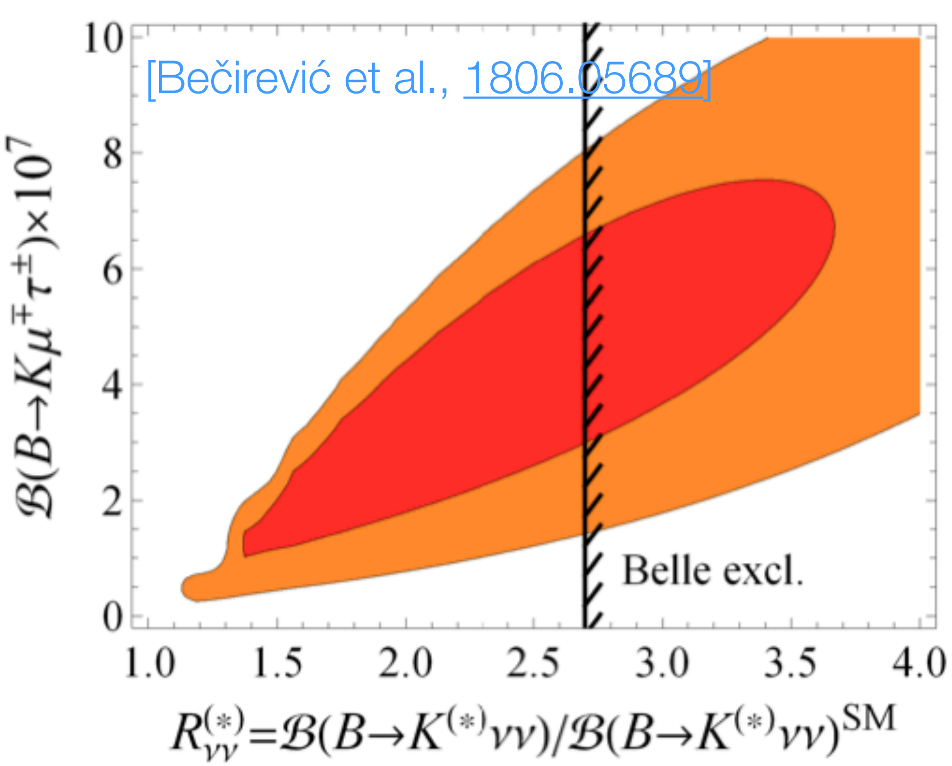

$R_2 + S_3$ $\quad \dfrac{\mathcal{B}(B \to K\nu\nu)}{\mathcal{B}(B \to K\nu\nu)_{\rm SM}} \gtrsim 1.5$

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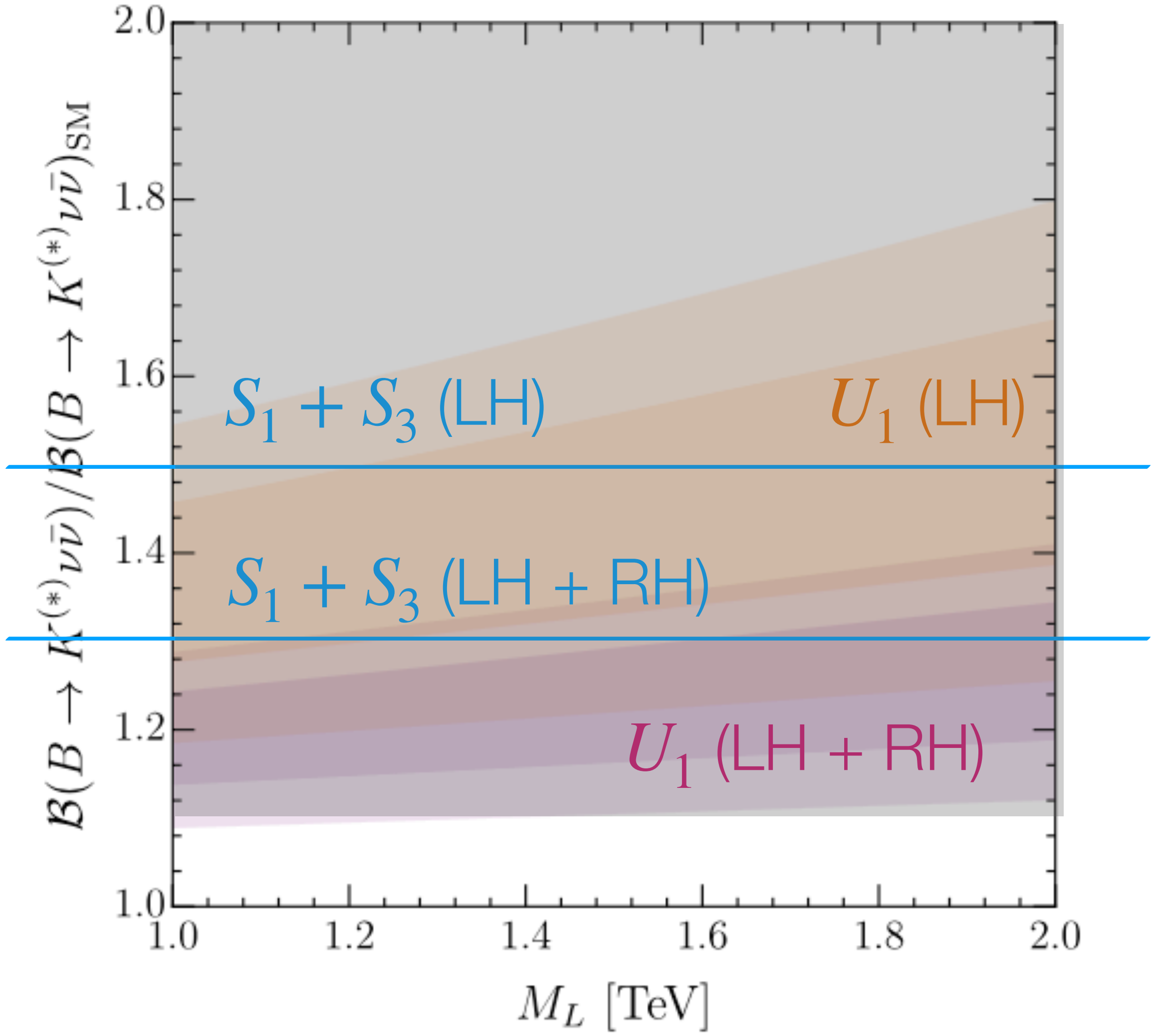

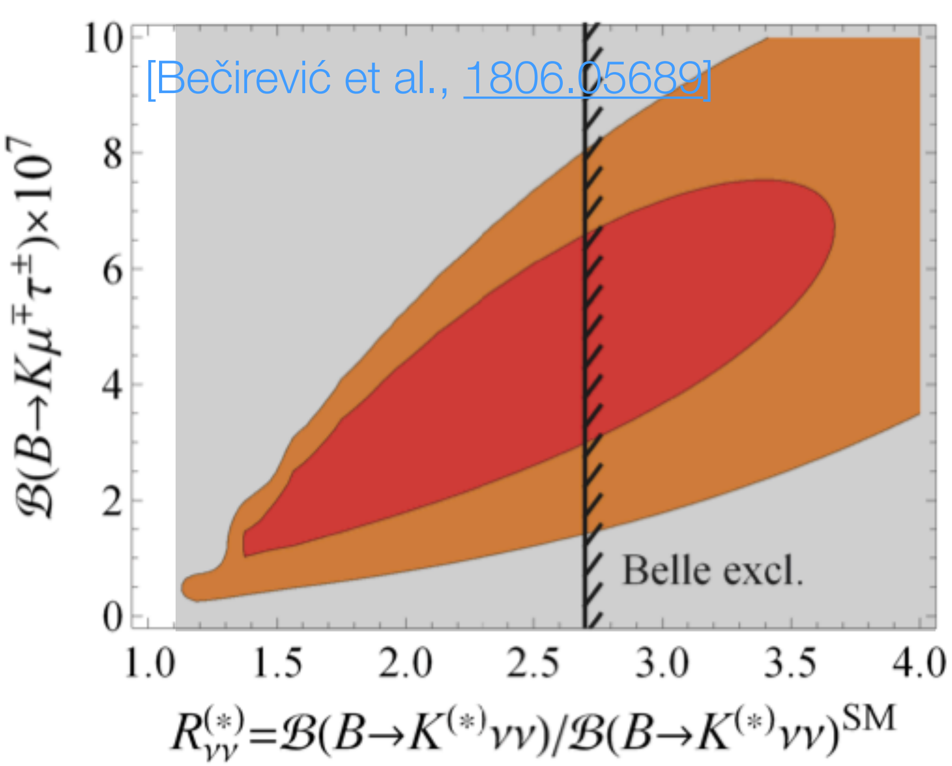

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Th: model building for $b \to sll$ is *very different* from that for $b \to sll$ and $b \to c\tau\nu$
without $R_{D^{(*)}}$ no obvious connection flavor anomalies - flavor hierarchies

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Looking forward to the plenty upcoming measurements from both the energy and intensity frontiers!