



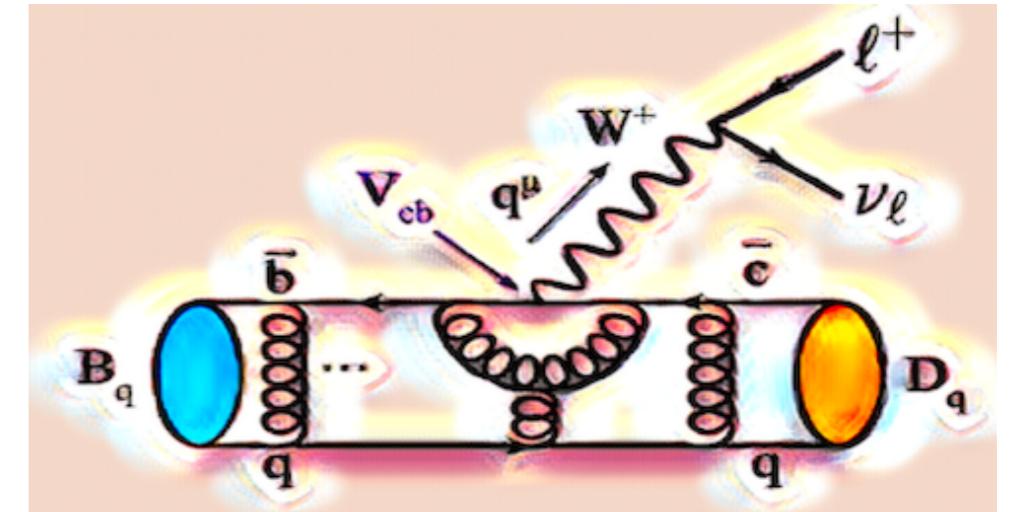
University of  
Zurich<sup>UZH</sup>

# Status of NP Model Building for $B$ -anomalies

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Ben A. Stefanek

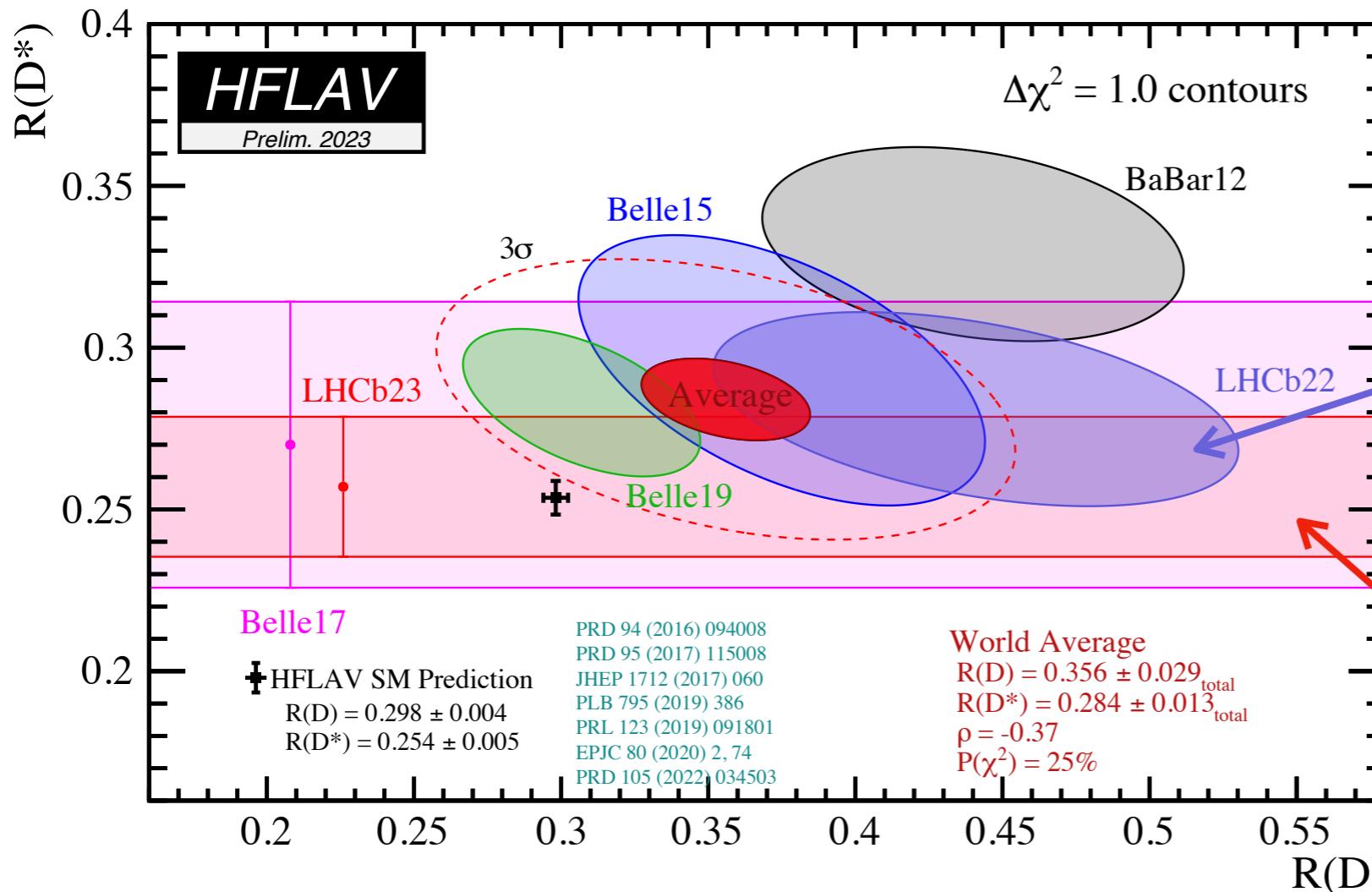
Physik-Institut  
University of Zurich



Beyond the Flavour Anomalies IV  
Casa Convalescencia, Barcelona  
April 19, 2023

# Charged-current B-anomalies

# Anomalies in $b \rightarrow c$ semi-leptonics: $R_D$ and $R_{D^*}$



$$R_{D^{(*)}} = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \rightarrow D^{(*)}\ell\bar{\nu})} \quad [\ell = e, \mu]$$

2022 LHCb  $\tau \rightarrow \mu$ : first joint measurement of  $R_D$  &  $R_{D^*}$  at a hadron collider. Only Run 1 data. [LHCb, [2302.02886](#)]

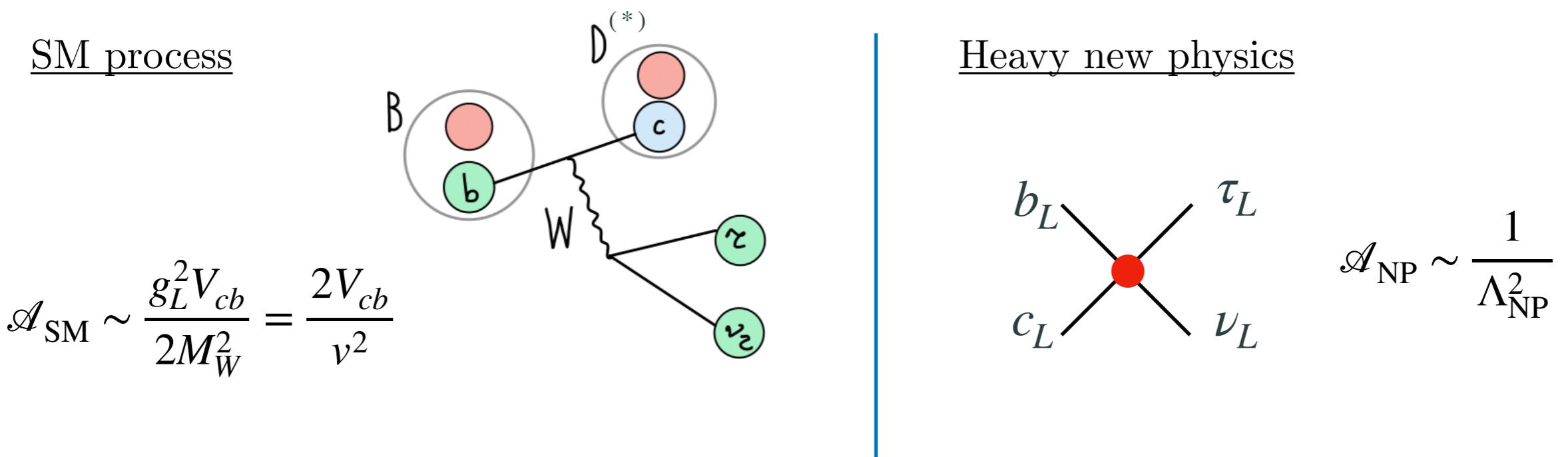
New! 2023 LHCb  $\tau \rightarrow$  had:  
 $R_{D^*}$  with Run 1 + partial Run 2 data. Hadronic taus.

- Theoretically semi-clean. Measurements by Babar, Belle, LHCb in good agreement.
- Enhancement of  $\sim 10\%$  over SM due to excess in tau mode:  $B \rightarrow D^{(*)}\tau\bar{\nu}_\tau$ .
- Combined,  $3.2\sigma$  tension w.r.t SM. Measurement of  $R_{\Lambda_c}/R_{\Lambda_c}^{\text{SM}} = 0.73 \pm 0.23$  reduces tension slightly. [LHCb, [2201.03497](#)]

# New physics in $b \rightarrow c\tau\nu$ decays

$$\delta R_{D^{(*)}} = R_{D^{(*)}}/R_{D^{(*)}}^{\text{SM}} - 1$$

- We need  $\sim 10\%$  of a tree-level SM process due to NP. Heavy NP should therefore also be tree-level to compete. Consider Fermi-like LH NP:

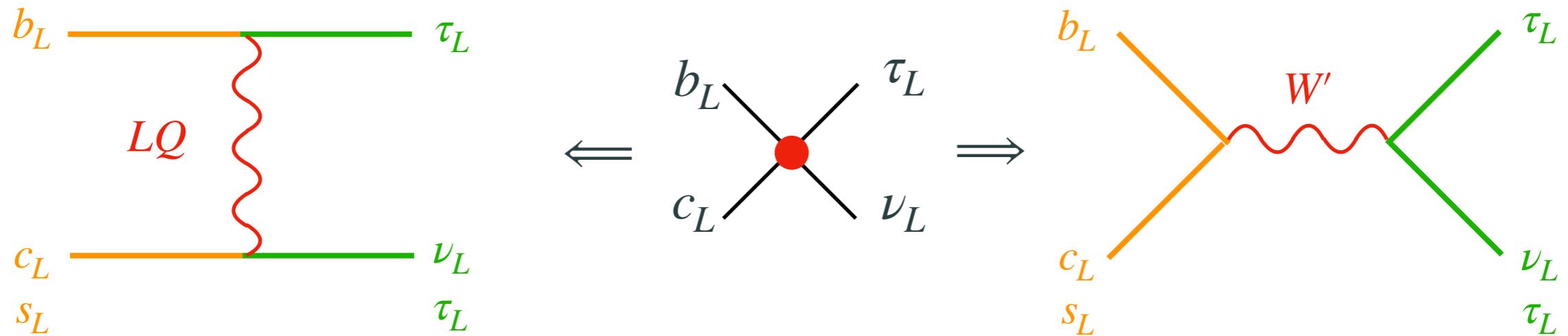


- The charged current  $B$ -anomalies are calling for a low NP scale!

$$2 \frac{\mathcal{A}_{\text{NP}}}{\mathcal{A}_{\text{SM}}} = \frac{v^2}{V_{cb} \Lambda_{\text{NP}}^2} \approx \delta R_{D^*} \implies \Lambda_{\text{NP}} \approx \frac{v}{\sqrt{V_{cb} \delta R_{D^*}}} \approx 3.6 \text{ TeV} \left( \frac{0.12}{\delta R_{D^*}} \right)^{1/2}$$

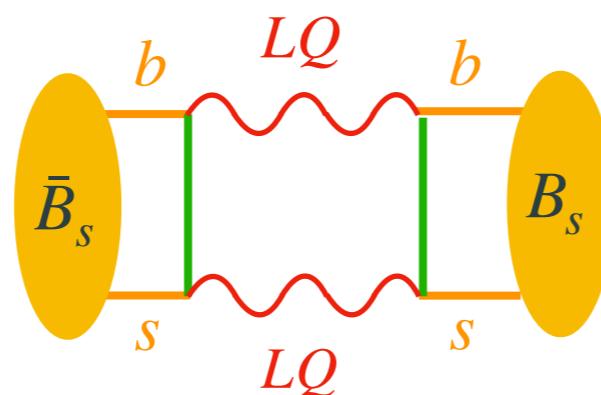
\*Low NP scale drives connection to high- $p_T$ : See Felix's talk (coming next)

# What kind of new particles could we have?

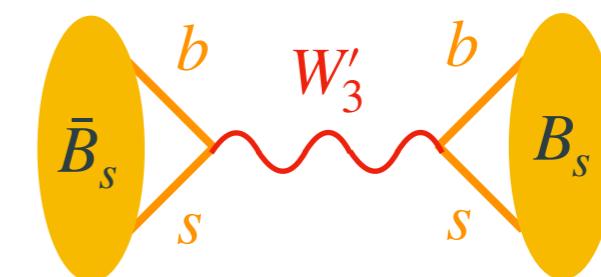


- LH NP  $\Rightarrow b \rightarrow s\tau\tau(\nu\nu)$  couplings. LQ's have two important advantages

1.  $\Delta F = 2$  :

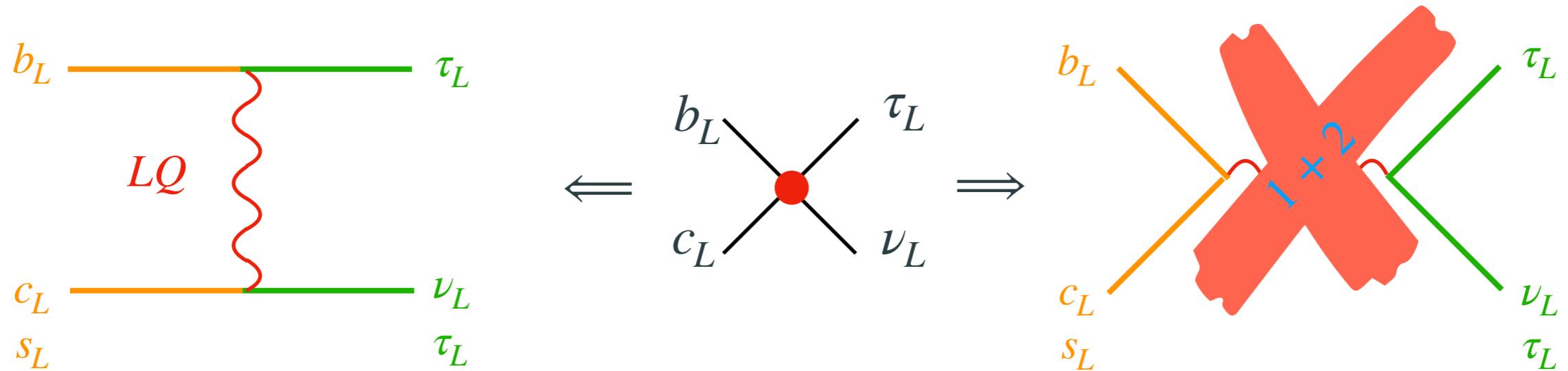


vs



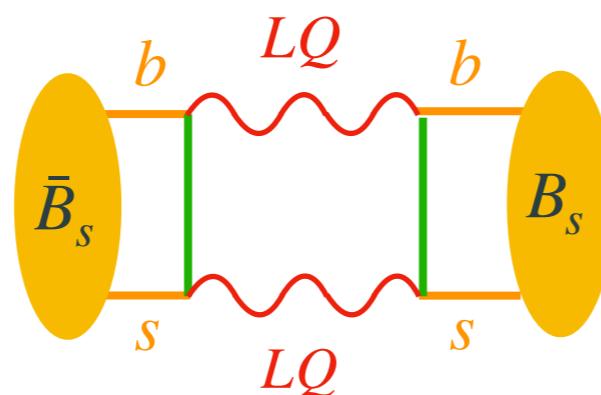
2. **Direct searches:** t-channel versus resonant s-channel production

# Only leptoquarks are viable mediators!

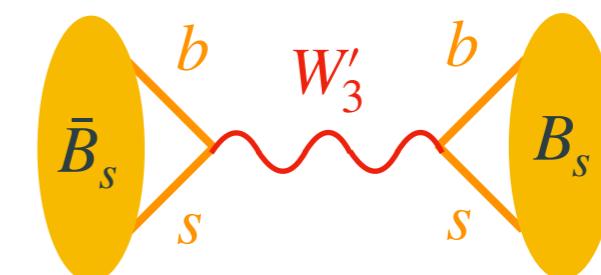


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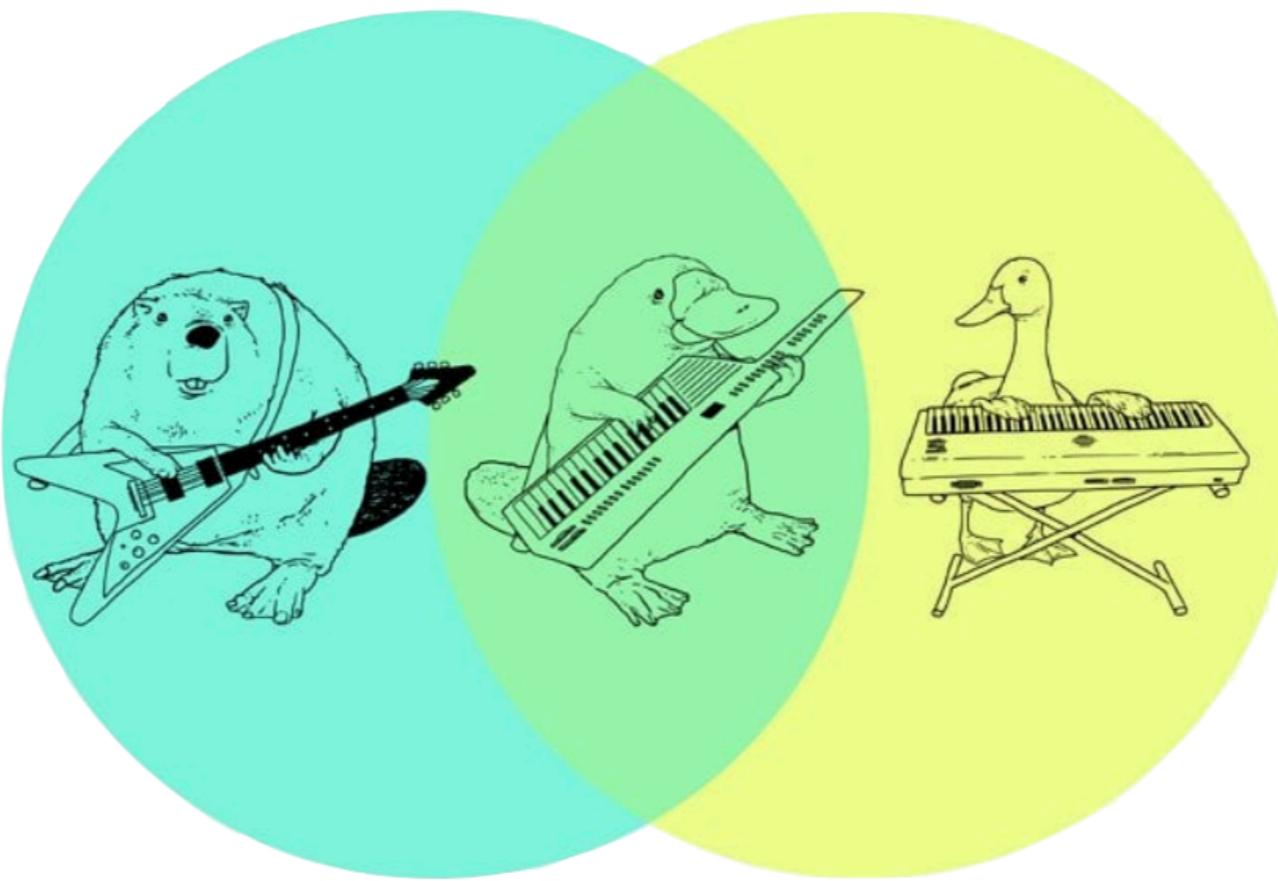


vs



2. **Direct searches:** t-channel versus resonant s-channel production

# What is a leptoquark?



Like a cross between a beaver & a duck is a platypus or a cross between a keyboard & a guitar is a keytar, a cross between a lepton & a quark is a leptoquark (LQ)

[Credit: Uli Haisch, La Thuile 2023 - Les Rencontres de Physique de la Vallée d'Aoste]

# Shopping for Leptoquarks



- There are three viable options on the leptoquark market:

Model	$R_{K(*)}$	$R_{D(*)}$	$R_{K(*)} \& R_{D(*)}$
$S_1 = (3, 1)_{-1/3}$	✗	✓	✗
$R_2 = (3, 2)_{7/6}$	✗	✓	✗
$\tilde{R}_2 = (3, 2)_{1/6}$	✗	✗	✗
$S_3 = (3, 3)_{-1/3}$	✓	✗	✗
$U_1 = (3, 1)_{2/3}$	✓	✓	✓
$U_3 = (3, 3)_{2/3}$	✓	✗	✗

[Angelescu, Bečirević, Faroughy, Sumensari, [1808.08179](#)]

## Scalar Leptoquarks:

★  $S_1 \sim (\bar{3}, 1, 1/3)$

[Crivellin, Muller, Ota [1703.09226](#); Buttazzo et al. [1706.07808](#); Marzocca [1803.10972](#), ...]

★  $R_2 \sim (3, 2, 7/6)$

[Bečirević et al., [1806.05689](#)]

## Vector Leptoquarks:

★  $U_1 \sim (3, 1, 2/3)$  (Massive spin-1, requires UV completion)

[di Luzio, Greljo, Nardecchia [1708.08450](#); Calibbi, Crivellin, Li [1709.00692](#); Bordone, Cornella, Fuentes-Martin, Isidori [1712.01368](#); Barbieri, Tesi, [1712.06844](#); Greljo, BAS, [1802.04274](#)]

# The low-energy $b \rightarrow c\tau\nu$ effective Lagrangian

$$\mathcal{L}_{\text{eff}}^{b \rightarrow c\tau\nu} = -\frac{2V_{cb}}{v^2} \left[ \overset{\text{SM}}{\overleftarrow{(1 + C_{V_L})(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L) + C_{V_R}(\bar{c}_R \gamma_\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_L)}}} + C_{S_L}(\bar{c}_R b_L)(\bar{\tau}_R \nu_L) + C_{S_R}(\bar{c}_L b_R)(\bar{\tau}_R \nu_L) + C_T(\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu} \nu_L) \right] + \text{h.c.}$$

Vector LQ:

$$U_1^\mu : C_{V_L}, C_{S_R}$$



Scalar LQs:

$$R_2 : C_{S_L} = 4C_T$$



$$S_1 : C_{V_L}, C_{S_L} = -4C_T$$



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$$R_2 : C_{S_L} = 4C_T$$

$$\delta R_D = + 7.1 \operatorname{Re}(C_T) + 17.2 |C_T|^2$$

$$\delta R_{D^*} = - 5.6 \operatorname{Re}(C_T) + 16.7 |C_T|^2$$

- This relation predicts opposite sign in  $R_D$  vs  $R_{D^*}$  due to interference with the SM.
- Since interference always goes as the real part, can make the WC's purely imaginary and then do  $R_{D^{(*)}}$  with NP squared.
- But then we need big WC's: **tension** with high- $p_T$  and EW precision observables.

\*See Felix's talk for more details (coming next).

# Neutral-current B-anomalies

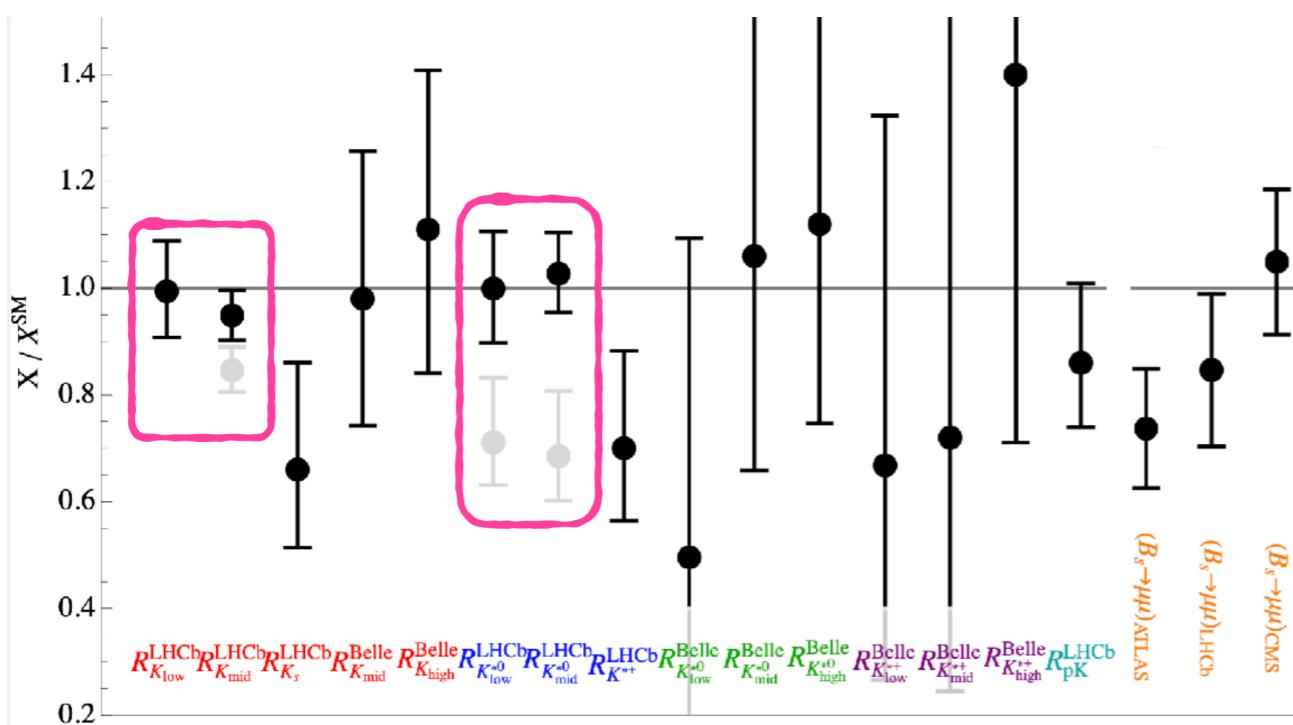
# The $b \rightarrow s\ell\ell$ anomalies before

- Until recently, two “types” of anomalies in  $b \rightarrow s\ell\ell$ :
  1.  $\mu/e$  universality ratios in  $B \rightarrow K^{(*)}ll$
  2. discrepancies in obs. with muons only  $\left\{ \begin{array}{l} \text{ang. obs. in } B^{(0,+)} \rightarrow K^{*(0,+)}\mu^+\mu^- \\ \text{BRs of } B \rightarrow K\mu^+\mu^-, B \rightarrow K^*\mu^+\mu^-, B_s \rightarrow \phi\mu^+\mu^- \end{array} \right.$

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- 12/2022: a second LHCb analysis of  $R_K$  &  $R_{K^*}$  establishes  $\mu/e$  lepton flavor universality in  $b \rightarrow s\ell\ell$  at  $\sim 5\%$  level [LHCb,221209152]



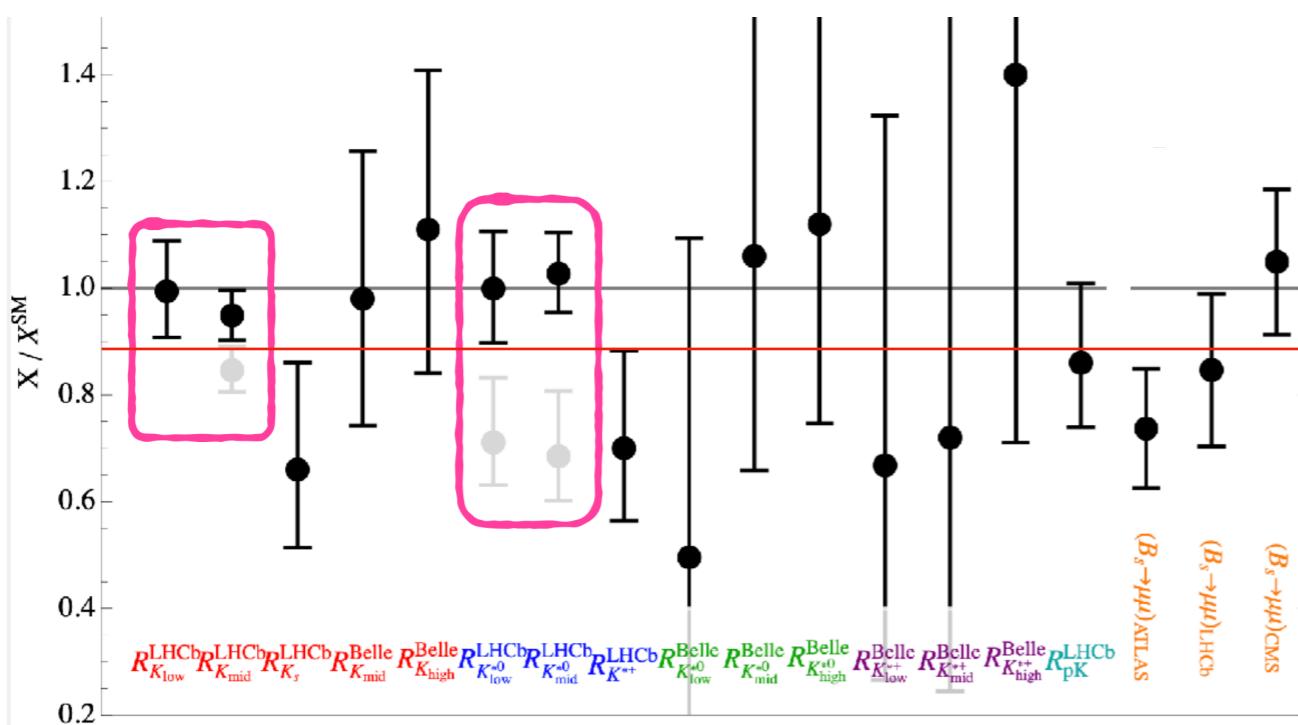
[compilation of  $b \rightarrow s\mu\mu$  clean observables  
as of Dec. 2022 (©David Marzocca)]

$$\begin{aligned} \text{low-}q^2 & \left\{ \begin{array}{l} R_K = 0.994^{+0.090}_{-0.082} \text{ (stat)}^{+0.029}_{-0.027} \text{ (syst)}, \\ R_{K^*} = 0.927^{+0.093}_{-0.087} \text{ (stat)}^{+0.036}_{-0.035} \text{ (syst)}, \end{array} \right. \\ \text{central-}q^2 & \left\{ \begin{array}{l} R_K = 0.949^{+0.042}_{-0.041} \text{ (stat)}^{+0.022}_{-0.022} \text{ (syst)}, \\ R_{K^*} = 1.027^{+0.072}_{-0.068} \text{ (stat)}^{+0.027}_{-0.026} \text{ (syst)}. \end{array} \right. \end{aligned}$$

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- Still room for small  $\mu/e$  lepton flavor violation at the  $\sim 10\%$  level

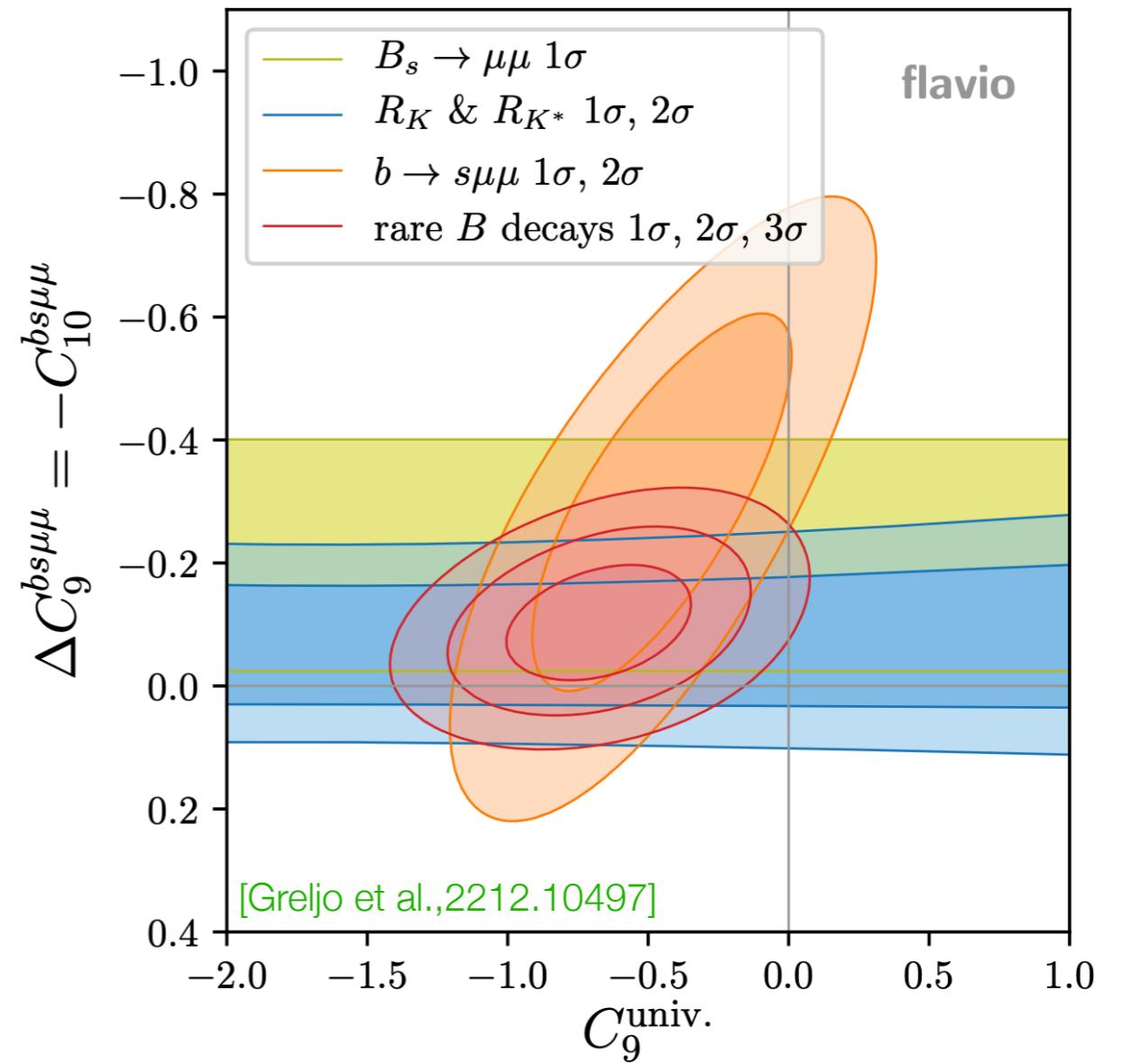
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$$O_9^{bs\mu\mu} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu} \gamma^\mu \mu)$$

$$O_{10}^{bs\mu\mu} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu} \gamma^\mu \gamma_5 \mu)$$

- Assuming **NP in muons only**, there's now *tension* between LFU ratios  $R_{K^{(*)}}$  and BR's +  $P'_5$



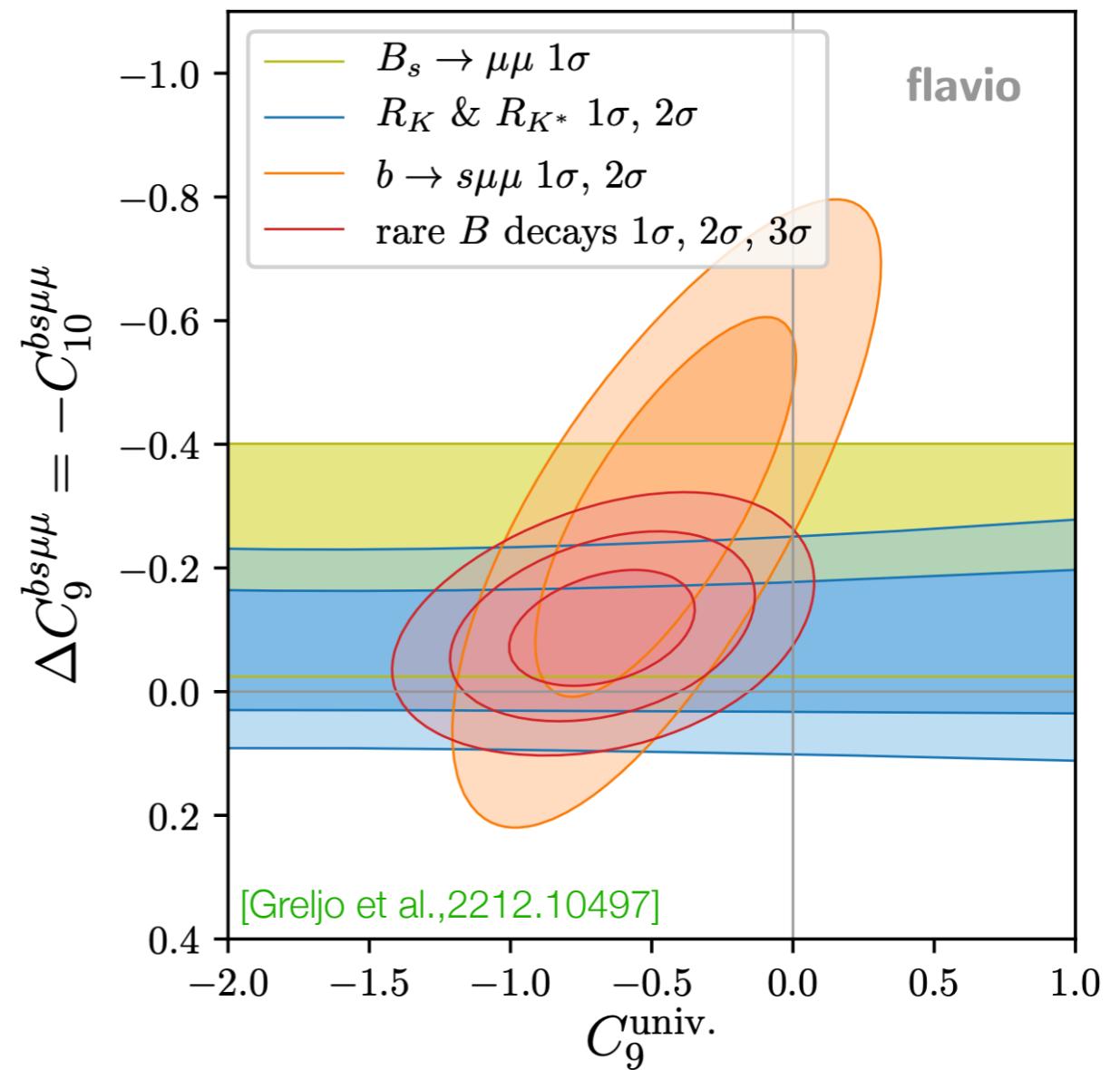
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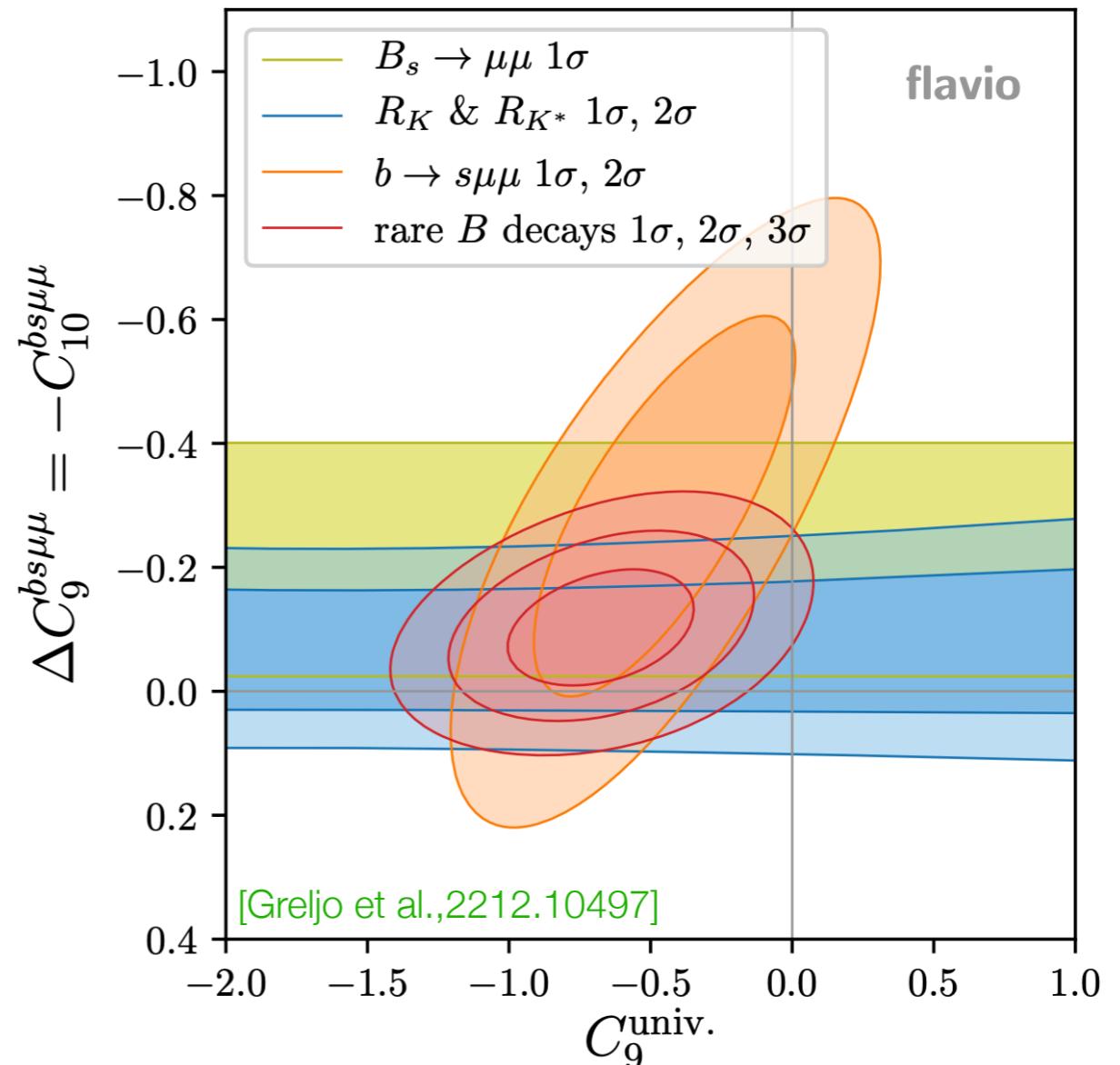
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\* But, non-trivial to distinguish from long-distance QCD (“charming penguins”)

To understand these contributions better:

- Improvement on theory side [Gubernari et al. 2206.03797, Ciuchini et al. 2212.10516]
- data-driven approach [see e.g. LHCb Coll., Eur.Phys.J.C 77(2017) 3,161]



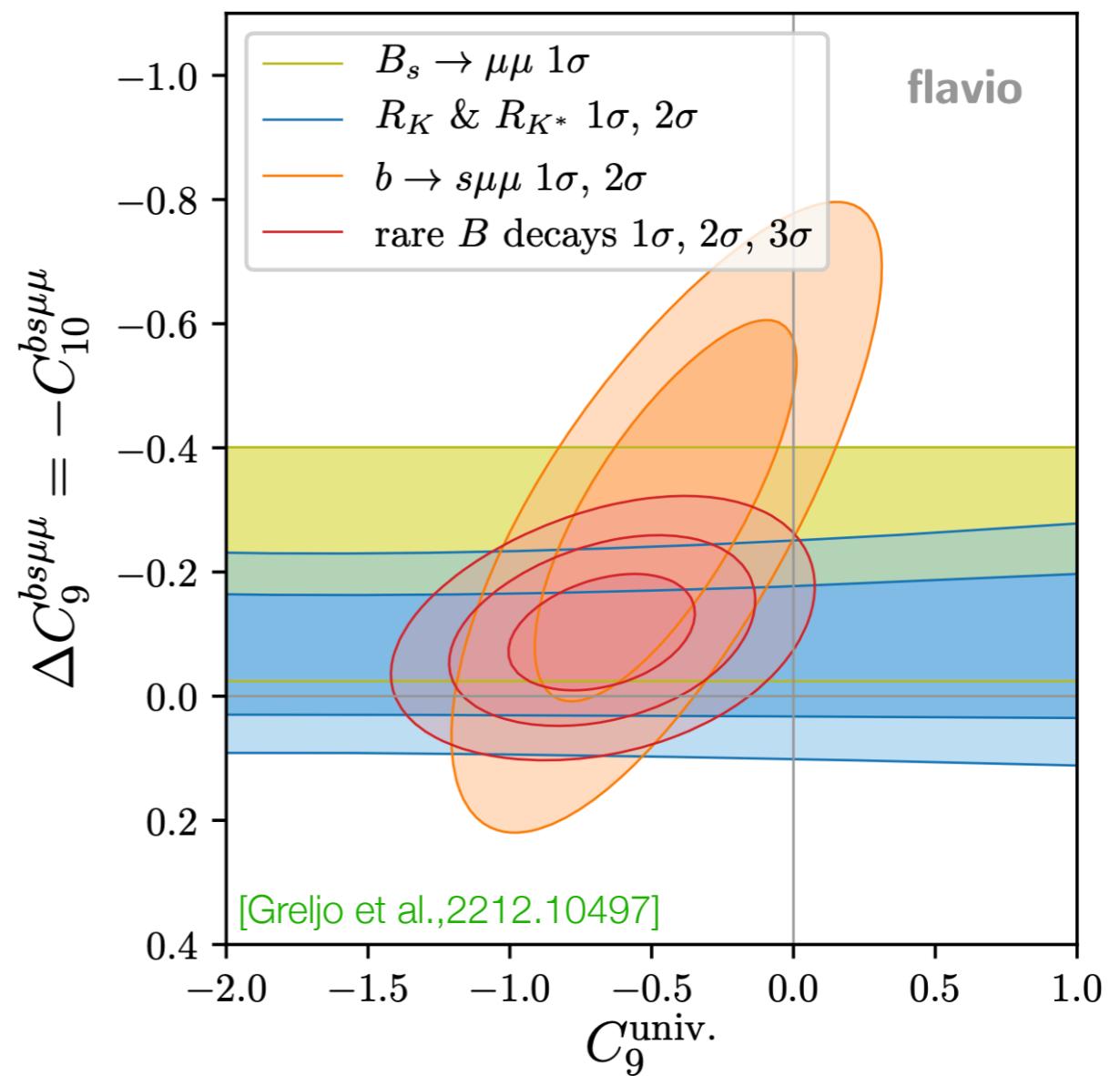
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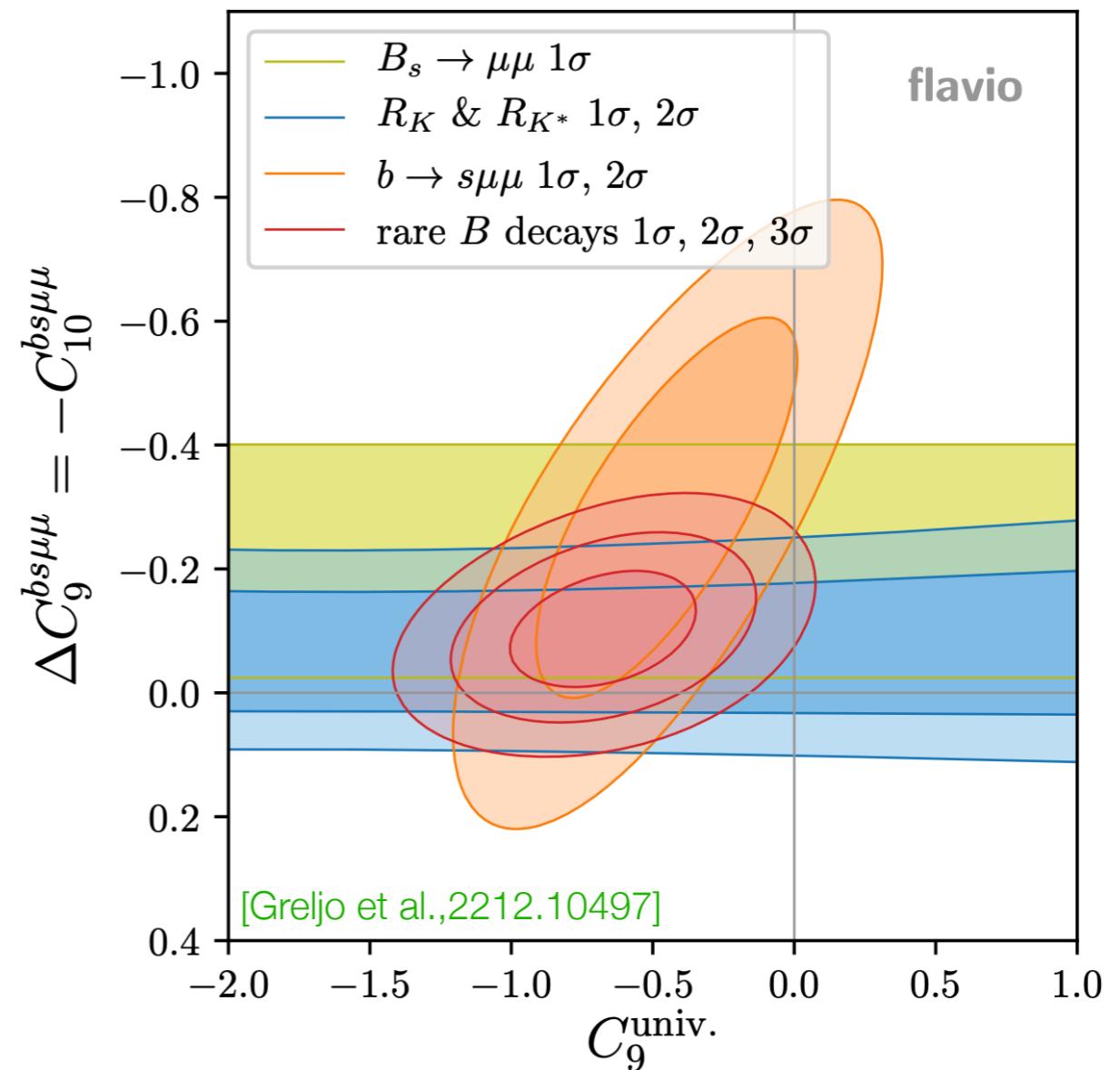
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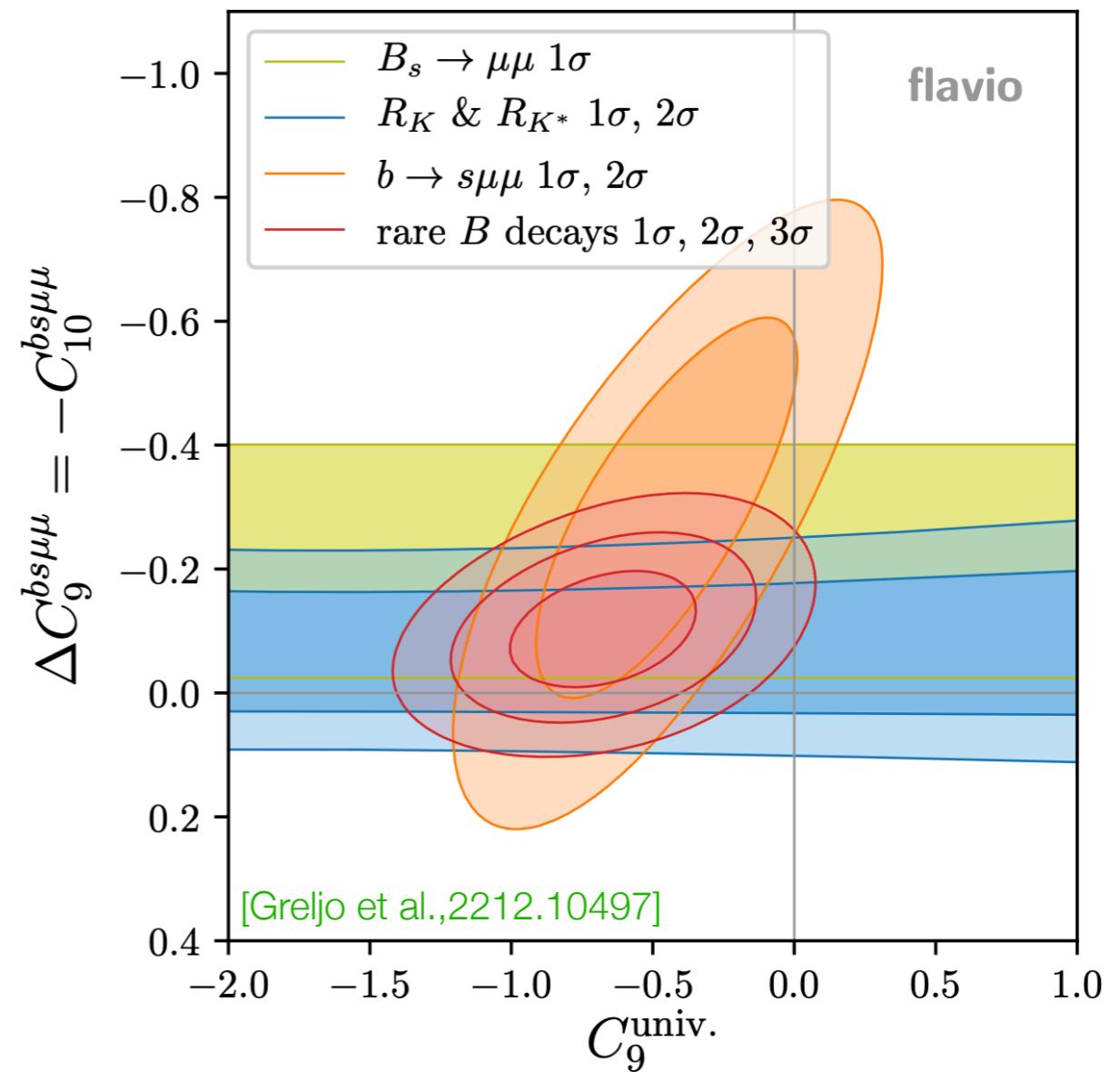
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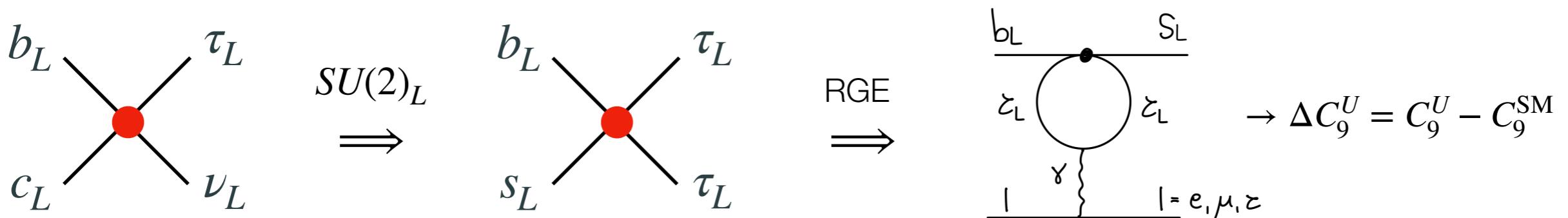
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- Still interesting to consider models for  $R_{D^{(*)}}$  (unaffected) that also give **flavor universal contributions** to the  $b \rightarrow s\ell\ell$  system.



# Connection: $b \rightarrow c\tau\nu$ and universal $b \rightarrow s\ell\ell$

- Some vector semi-leptonics that explain the charged-current anomalies give a *flavor universal* effect in  $b \rightarrow s\ell\ell$  via RGE:



$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i^\ell O_i^\ell$$

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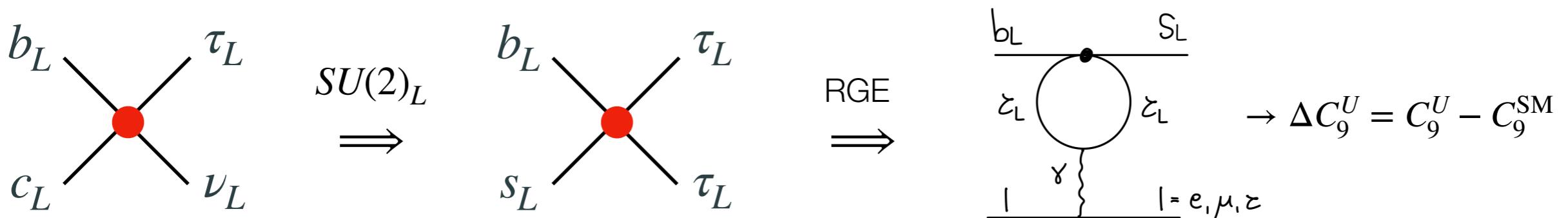
- Leading-log running in SM gauge couplings gives

$$\Delta C_9^U = \frac{v_{\text{EW}}^2}{3V_{tb}V_{ts}^*} \left( [C_{lq}^{(3)}]_{\alpha\alpha 23} + [C_{lq}^{(1)}]_{\alpha\alpha 23} + [C_{qe}]_{23\alpha\alpha} \right) \log \left( \frac{m_b^2}{M^2} \right)$$

\*In general, sum over lepton flavors  $\alpha$ . For third-family NP, we take just  $\alpha = 3$ .

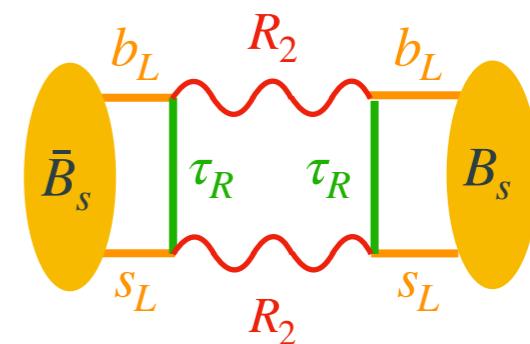
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$U_1$	$S_1$	$R_2$
$C_{lq}^{(3)} = C_{lq}^{(1)}$	$C_{lq}^{(3)} = -C_{lq}^{(1)}$	Only $[C_{qe}]_{3333}$

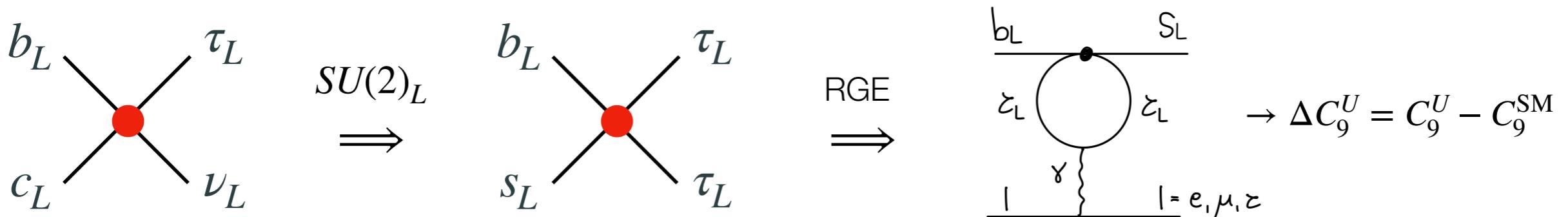


\*With both  $[C_{qe}]_{3333}$  &  $[C_{qe}]_{2333}$  active

[Bobeth, Haisch, [1109.1826](#); Crivellin et al., [1807.02068](#); Algueró et al., [1809.08447](#)] 14

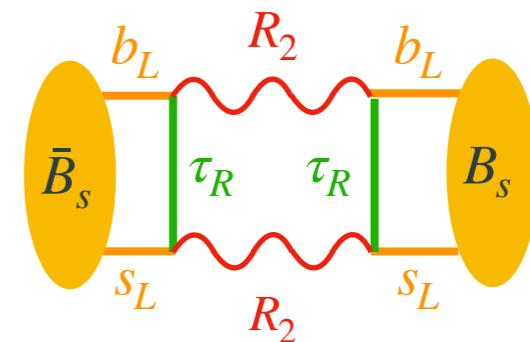
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# Simplified model for $U_1$ leptoquark

$U_1 \sim (3, 1, 2/3)$

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[ (\bar{q}_L^3 \gamma_\mu \ell_L^3) + \beta_L^{s\tau} (\bar{q}_L^2 \gamma_\mu \ell_L^3) + \beta_R^{b\tau} (\bar{b}_R \gamma_\mu \tau_R) \right] + \text{h.c.}$$



$U(2)_q$ -breaking  $\sim O(V_{cb})$

# Simplified model for $U_1$ leptoquark

$U_1 \sim (3, 1, 2/3)$

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[ (\bar{q}_L^3 \gamma_\mu \ell_L^3) + \beta_L^{s\tau} (\bar{q}_L^2 \gamma_\mu \ell_L^3) + \beta_R^{b\tau} (\bar{b}_R \gamma_\mu \tau_R) \right] + \text{h.c.}$$

Integrate out the  $U_1$  LQ:  $\frac{1}{\Lambda_{\text{NP}}^2} = \frac{g_U^2}{2M_U^2}$



$$\mathcal{L}_{b \rightarrow c \tau \bar{\nu}} = -\frac{2}{v^2} V_{cb} \left[ \left( 1 + C_{LL}^c \right) (\bar{c}_L \gamma_\mu b_L) (\bar{\tau}_L \gamma^\mu \nu_L) - 2 C_{LR}^c (\bar{c}_L b_R) (\bar{\tau}_R \nu_L) \right]$$

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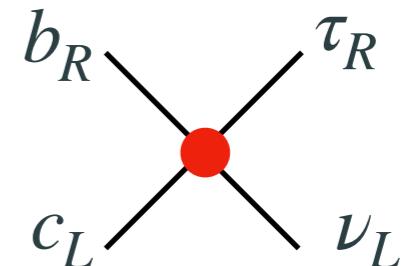
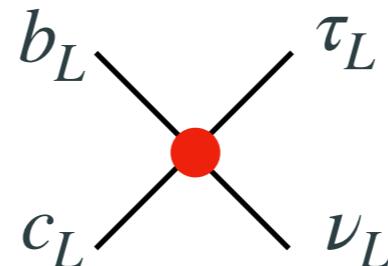
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↓ **RUNNING to EW SCALE + MATCHING** ↓

$$\mathcal{L}_{b \rightarrow c \tau \bar{\nu}} = -\frac{2}{v^2} V_{cb} \left[ \left( 1 + C_{LL}^c \right) (\bar{c}_L \gamma_\mu b_L) (\bar{\tau}_L \gamma^\mu \nu_L) - 2 C_{LR}^c (\bar{c}_L b_R) (\bar{\tau}_R \nu_L) \right]$$

Contact interaction:



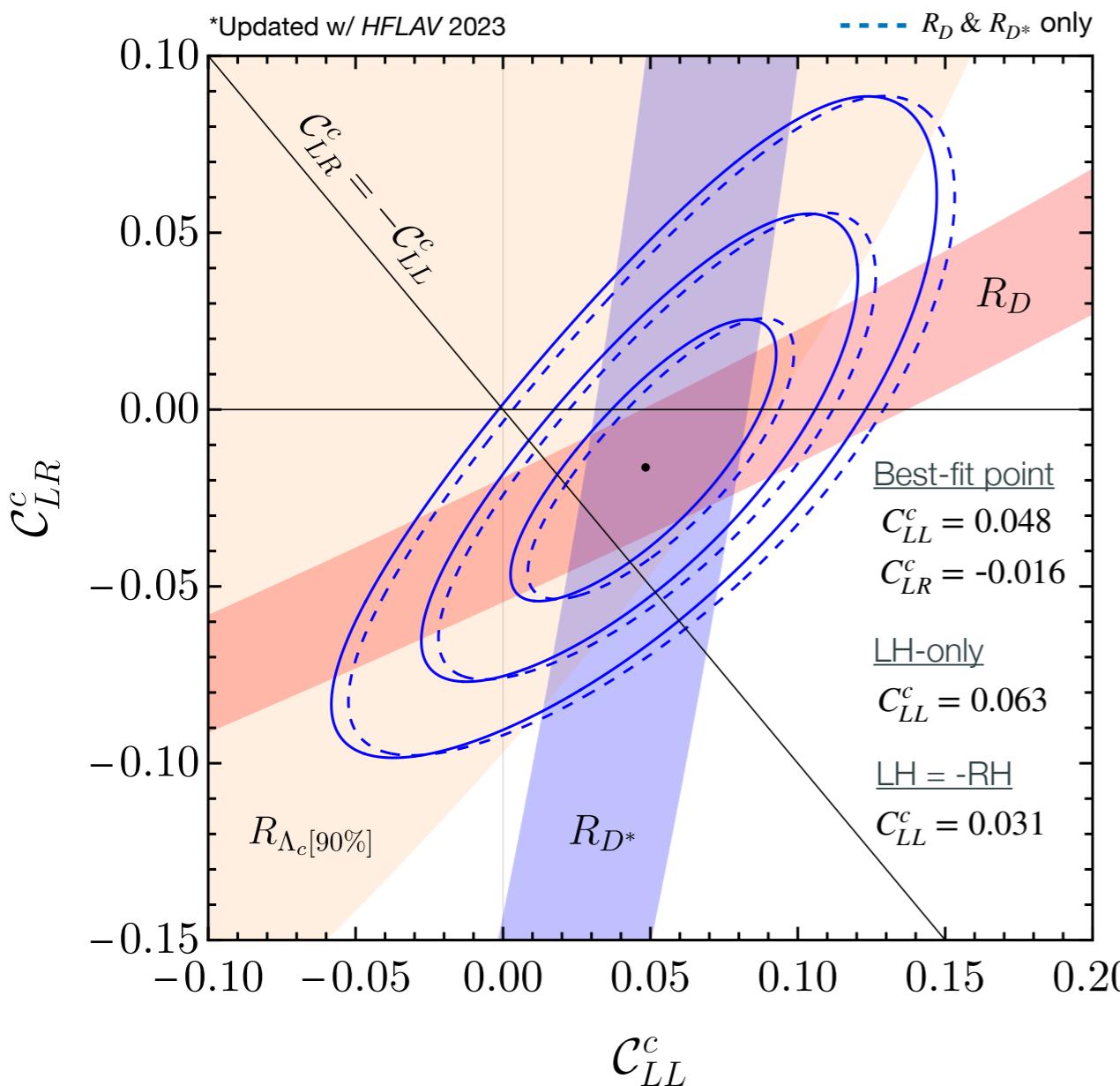
Low-energy WC's  $\leftrightarrow$  Model parameters:

$$C_{LL}^c = \frac{g_U^2 v^2}{4M_U^2} \left( 1 + \frac{V_{cs}}{V_{cb}} \beta_L^{s\tau} \right), \quad C_{LR}^c = \beta_R^{b\tau*} C_{LL}^c$$

# Low-energy fit for $U_1$ leptoquark model

$U_1 \sim (3, 1, 2/3)$

$$\mathcal{L}_{b \rightarrow c\tau\bar{\nu}} = -\frac{2}{v^2} V_{cb} \left[ \left(1 + C_{LL}^c\right) (\bar{c}_L \gamma_\mu b_L) (\bar{\tau}_L \gamma^\mu \nu_L) - 2 C_{LR}^c (\bar{c}_L b_R) (\bar{\tau}_R \nu_L) \right]$$



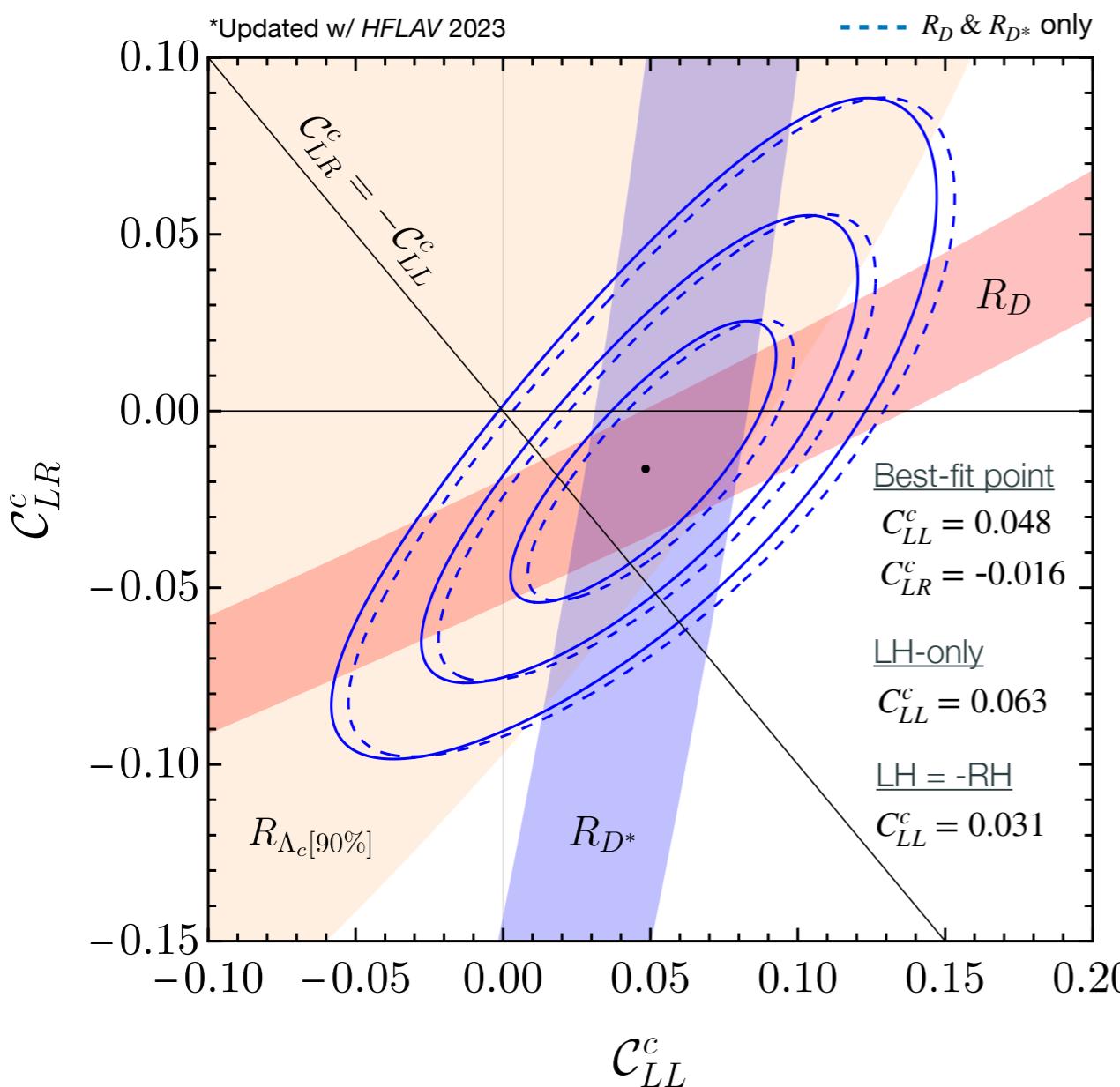
$$\delta R_{D^{(*)}} \approx 2C_{LL}^c - a_{D^{(*)}} C_{LR}^c \quad \begin{cases} a_D \approx 3.00 \\ a_{D^*} \approx 0.24 \end{cases}$$

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Matching: NP scale and U(2)-breaking

$$\frac{1}{\Lambda_{NP}^2} = \frac{g_U^2}{2M_U^2}, \quad V_q = \beta_L^{st}$$

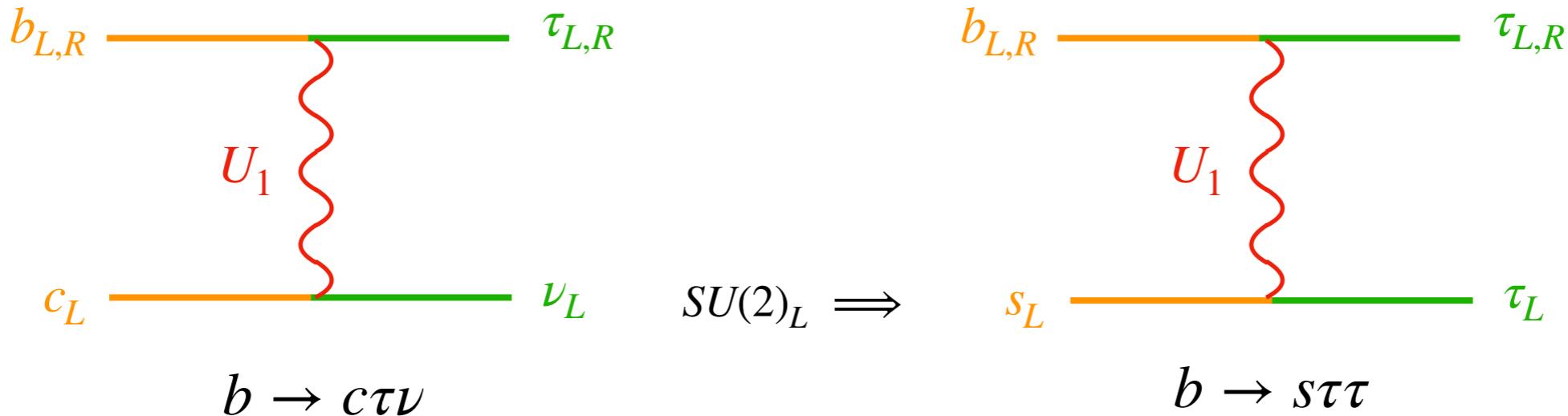
New physics scale preferred by low-energy fit:

$$\Lambda_{NP} \approx \{1.2, 1.5, 1.8\} \text{ TeV}, \quad (V_q = 0.1)$$

{LH-only, BFP, LH=-RH}

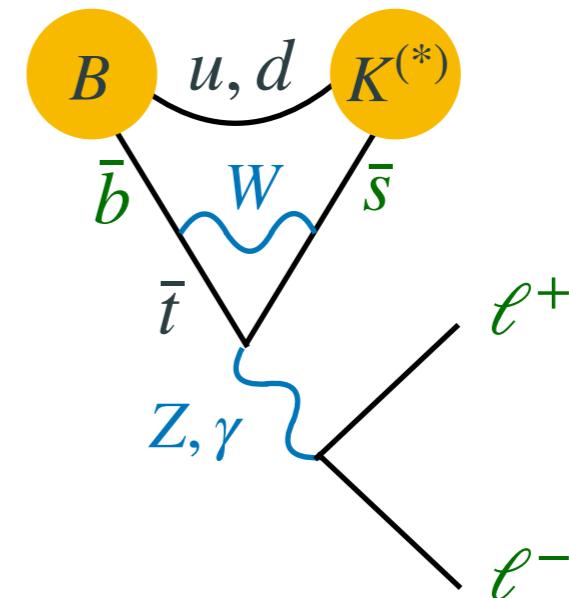
# $U_1$ connects $R_{D^{(*)}}$ to $b \rightarrow s\tau\tau$ observables

- We have tree-level effects in  $b \rightarrow s\tau\tau$  connected to the size of  $R_{D^{(*)}}$



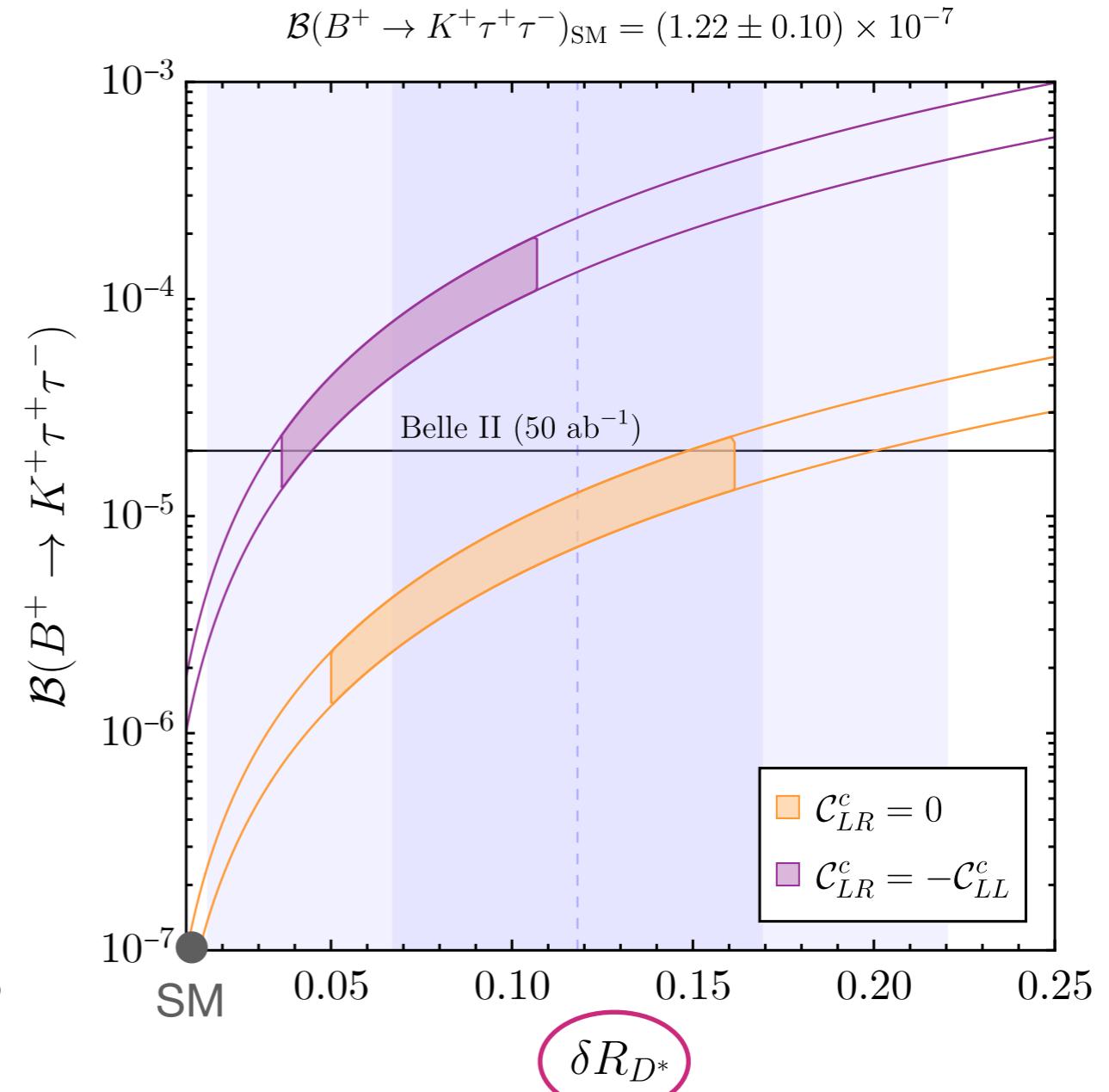
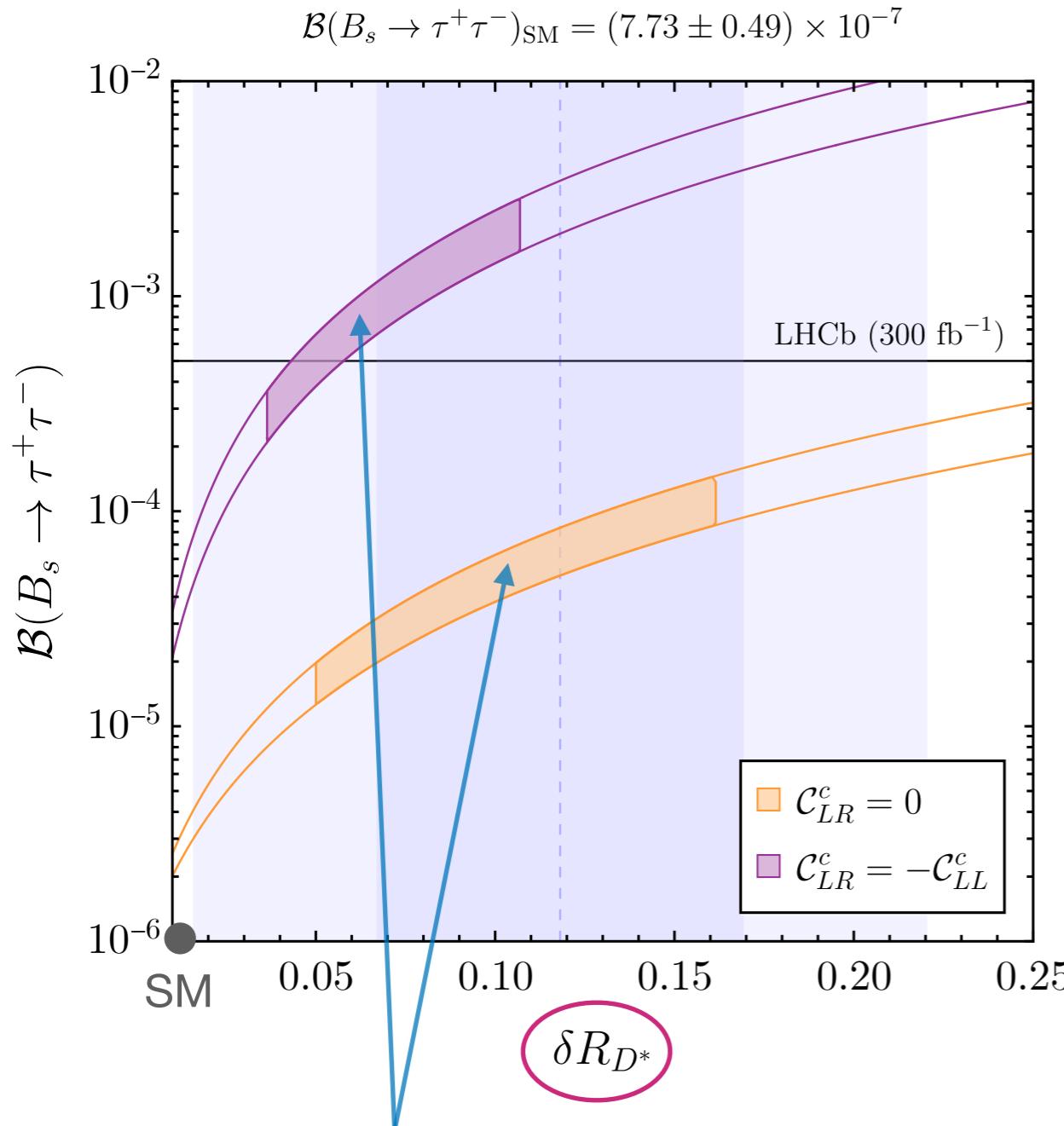
- Since  $b \rightarrow s\tau\tau$  is a FCNC, it is a 1-loop process in the SM. We therefore expect a huge NP enhancement in  $b \rightarrow s\tau\tau$ !

$$\frac{\mathcal{B}(B \rightarrow K^{(*)}\tau\tau)}{\mathcal{B}(B \rightarrow K^{(*)}\tau\tau)_{\text{SM}}} \sim 16\pi^2 \frac{R_{D^{(*)}}}{R_{D^{(*)}}^{\text{SM}}}$$



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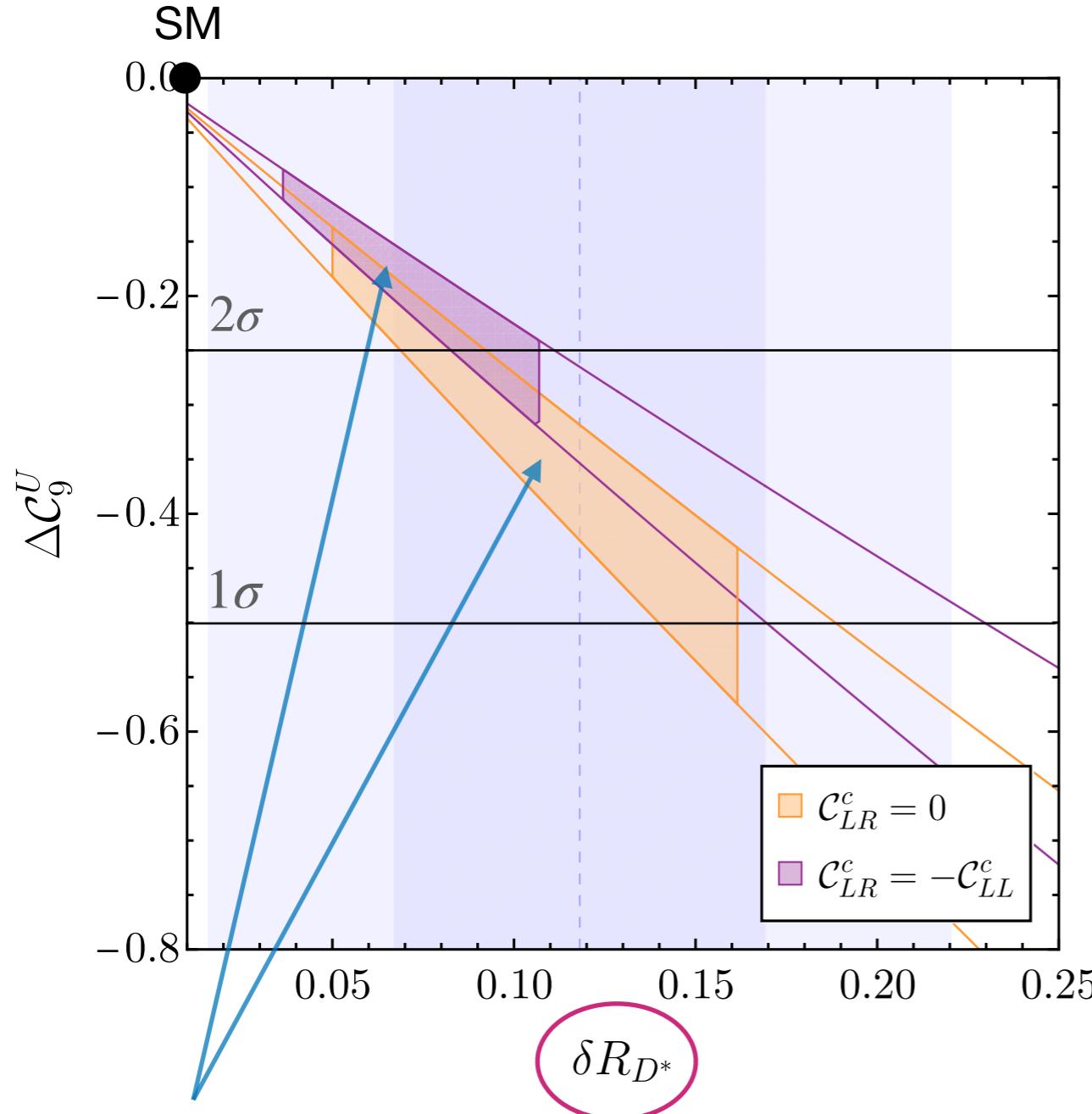


Updated 90% CL region preferred by low-energy  $b \rightarrow c\tau\nu$  data [2210.13422](#)

[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, [2210.13422](#)]

# $U_1$ connects $R_{D^{(*)}}$ to universal $b \rightarrow s\ell\ell$ observables

- Large  $b \rightarrow s\tau\tau$  implies a sizable *flavor universal* loop effect in  $b \rightarrow s\ell\ell$ !

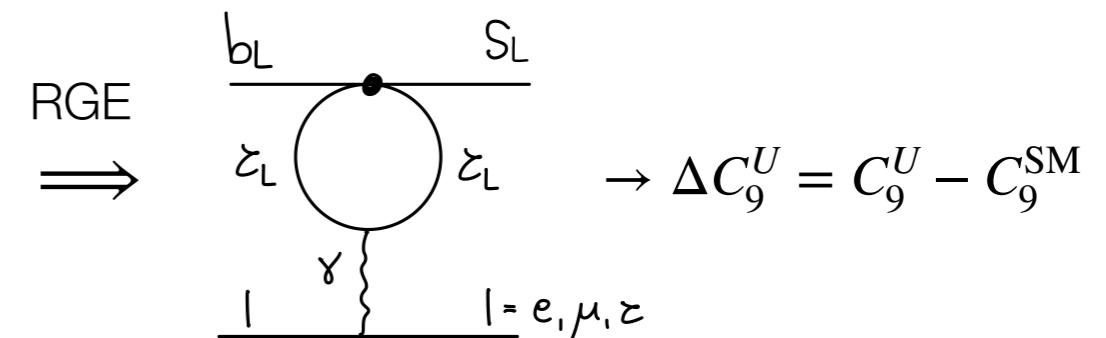


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[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, [2210.13422](#)]

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

$$O_9^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell} \gamma^\mu \ell)$$



“Dirty”  $b \rightarrow s\ell^+\ell^-$  data prefers:  
 $\Delta C_9^U \approx 0.75 \pm 0.25$

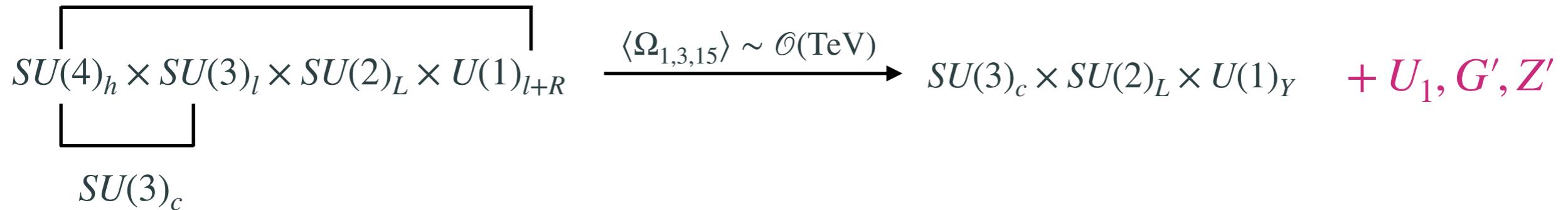
[Altmannshofer, Stangl [2103.13370](#)  
Bobeth, Haisch, [1109.1826](#); Crivellin  
et al., [1807.02068](#);  
Algueró et al., [1809.08447](#)]

# UV Completion for the $U_1$ Leptoquark

# UV Model: New flavor non-universal gauge interactions

Based on “4321” gauge symmetry:

$$U(1)_Y$$



$$SU(4) \sim \begin{pmatrix} G^a & U^\alpha \\ (U^\alpha)^* & Z' \end{pmatrix}$$

# UV Model: New flavor non-universal gauge interactions

Based on “4321” gauge symmetry:

$$U(1)_Y$$

$$SU(4)_h \times SU(3)_l \times SU(2)_L \times U(1)_{l+R} \xrightarrow{\langle\Omega_{1,3,15}\rangle \sim \mathcal{O}(\text{TeV})} SU(3)_c \times SU(2)_L \times U(1)_Y + U_1, G', Z'$$

$SU(3)_c$

Third-family quark-lepton unification at the TeV scale: [Greljo, BAS, [1802.04274](#)]

$$\psi_L \sim \begin{pmatrix} q_L^3 \\ \ell_L^3 \end{pmatrix} \quad \psi_R^+ \sim \begin{pmatrix} u_R^3 \\ \nu_R^3 \end{pmatrix} \quad \psi_R^- \sim \begin{pmatrix} d_R^3 \\ e_R^3 \end{pmatrix}$$

- 3rd family charged under  $SU(4)_h$   
⇒ Direct NP couplings (L+R)
- Light families under 321 (SM-like)
- Accidental approximate  $U(2)^5$  flavor symmetry:  $\psi = (\psi_1 \ \psi_2 \ \psi_3)$
- Good starting point for CKM

Leptons as the fourth “color”

[Pati, Salam, [Phys. Rev. D10 \(1974\) 275](#)  
(only 7 years after the SM was proposed)]

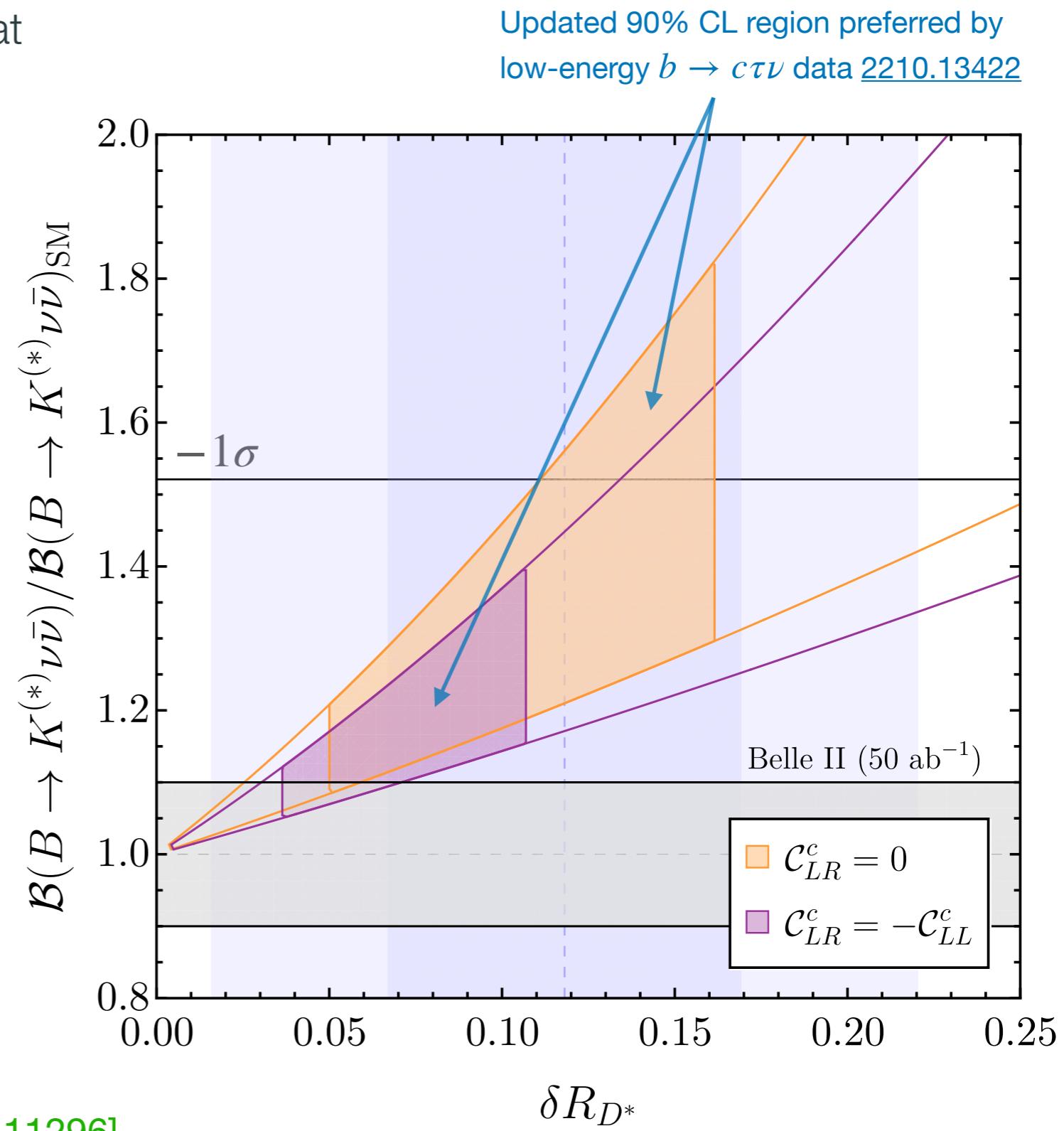
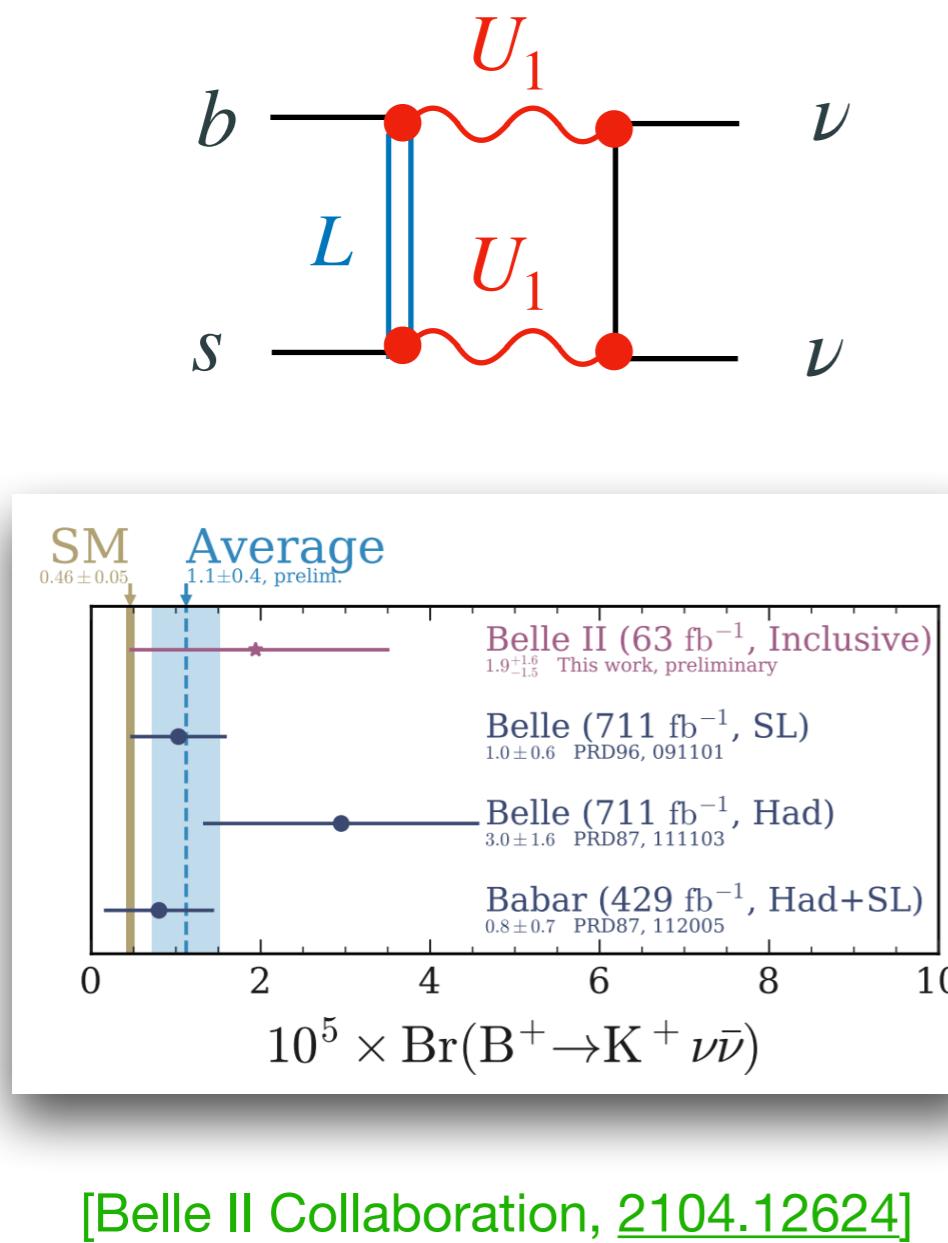
4321 models

[di Luzio, Greljo, Nardecchia [1708.08450](#)  
Bordone, Cornella, Fuentes-Martin, Isidori  
[1712.01368](#), [1805.09328](#);  
Greljo, BAS, [1802.04274](#);  
Cornella, Fuentes-Martin, Isidori [1903.11517](#)]

$$\psi_{L,R} = \begin{bmatrix} q_{L,R}^1 \\ q_{L,R}^2 \\ q_{L,R}^3 \\ l_{L,R} \end{bmatrix}$$

# Important 1-loop effects: $B \rightarrow K^{(*)}\nu\bar{\nu}$ (4321 Model)

- Some (important) effects appear only at one loop. For  $U_1$ , requires UV model!



[Fuentes-Martin, Isidori, König, Selimovic, [2009.11296](#)]

# Wrapping Up

## Overview of ongoing LFU measurements

mode	Run 1: 3 fb <sup>-1</sup> at 7/8 TeV		Run 2: 6 fb <sup>-1</sup> at 13 TeV	
	muonic	hadronic	muonic	hadronic
$R(D^+)$	✗	✗	✗	✗
$R(D^0)$	✓	✗	✗	✗
$R(D^*)$	✓	✓	✗	✗
$R(\Lambda_c)$	✗	✓	✗	✗
$R(\Lambda_c^*)$	✗	✗	✗	✗
$R(J/\phi)$	✓	✗	✗	✗
$R(D_s^+)$	✗	✗	✗	✗
$R(D_s^{*+})$	✗	✗	✗	✗

- So far only published Run 1 results; Run 2 has four times as much data
- Many analyses in progress; no timelines
- Work ongoing also in  $b \rightarrow u$  sector; and excited states:  $\mathcal{R}(D^{**}), \mathcal{R}(D_s^{**})$

Suzanne Klaver

LFU in charged-current  $b$  decays

Implication WS 19 October 2022 18

- Also all of these processes yet to be analyzed (or only Run 1 data). Since the underlying partonic  $b \rightarrow c\tau\nu$  process is the same, NP expected in all of these!

# Conclusions

- The tension in the LFU ratios  $R_{D^{(*)}}$  remains an interesting hint of NP at the TeV scale. If we take it seriously, leptoquark models are the only viable mediators.  
**Important:** These models did not change much without  $R_{K^{(*)}}$ !

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Thanks a lot for your attention!

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# Backup Slides

# UV Model: New colored particles and EW observables

- In addition to the  $U_1$  LQ, we also get neutral  $G'$ ,  $Z'$  vectors.
- We also need a vector-like quark and lepton  $Q$ ,  $L$  for fermion mixing.

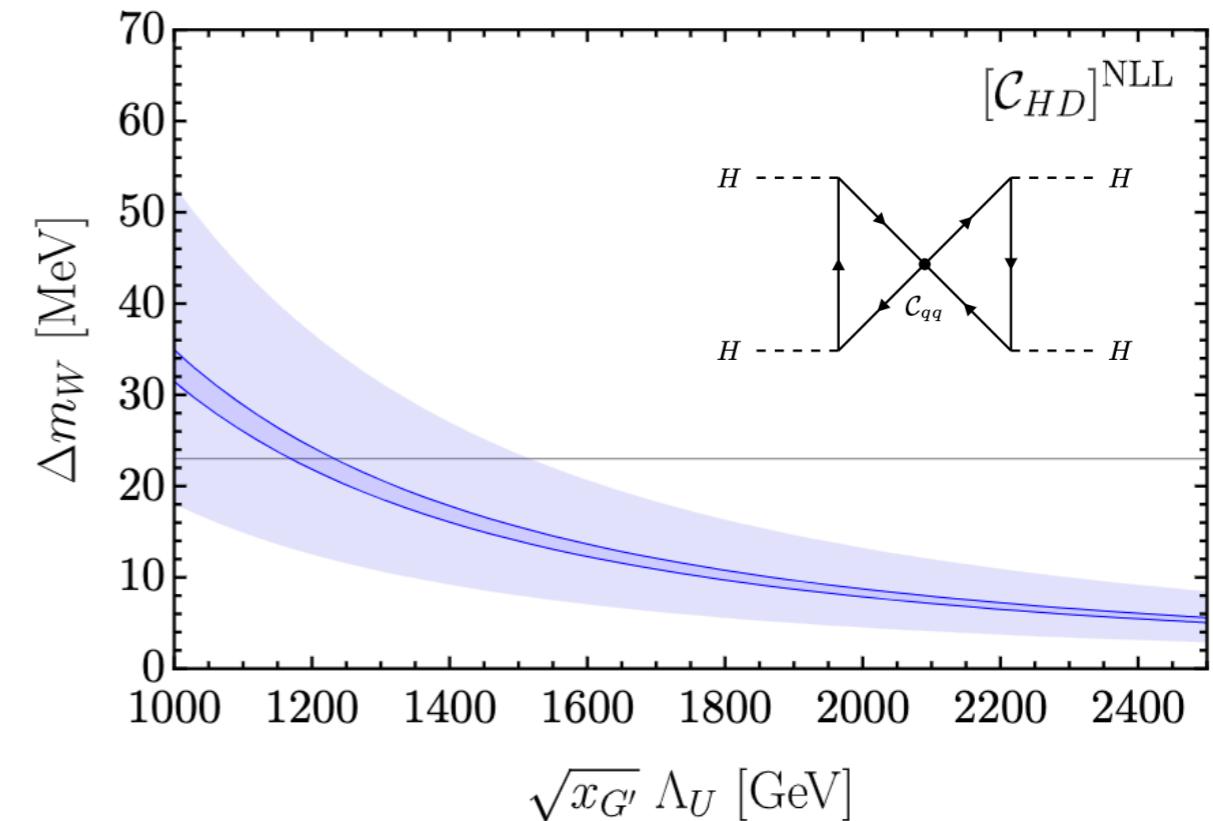
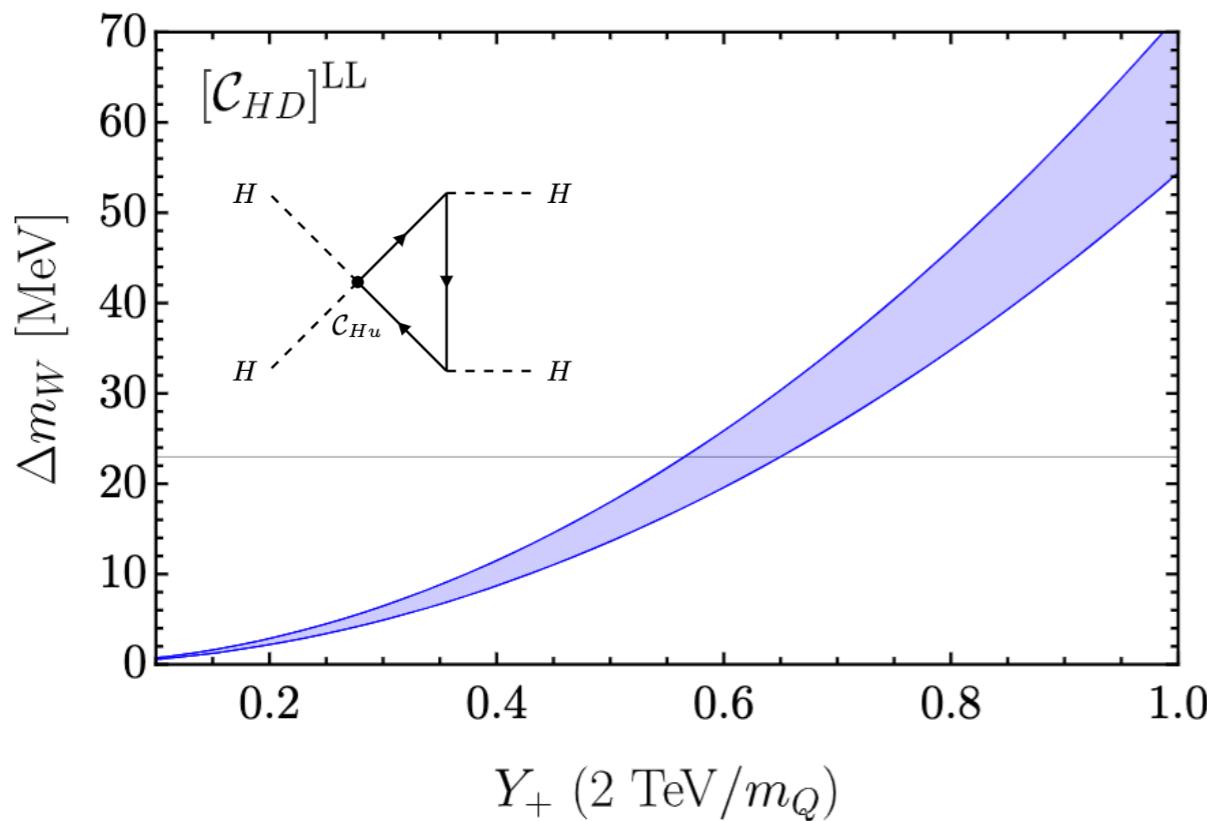
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- In addition to the  $U_1$  LQ, we also get neutral  $G'$ ,  $Z'$  vectors.
- We also need a vector-like quark and lepton  $Q, L$  for fermion mixing.
- New colored states  $Q, G'$  give sizable shifts in the W-mass via RGE effects.

$$\frac{\Delta m_W}{m_W} \supset -\frac{v^2}{4} \frac{g_L^2}{g_L^2 - g_Y^2} C_{HD}$$

$$\mathcal{O}_{HD} = |H^\dagger D_\mu H|^2$$

$$\alpha T = -\frac{v^2}{2} C_{HD}$$



- Full EW fit in 4321 model: [Allwicher, Isidori, Lizana, Selimovic, BAS, [2302.11584](#)]

# The low-energy $b \rightarrow c\tau\nu$ effective Lagrangian

$$\mathcal{L}_{\text{eff}}^{b \rightarrow c\tau\nu} = -\frac{2V_{cb}}{v^2} \left[ (\overset{\text{SM}}{\cancel{(1 + C_{V_L})}} (\bar{c}_L \gamma_\mu b_L) (\bar{\tau}_L \gamma_\mu \nu_L) + C_{V_R} (\bar{c}_R \gamma_\mu b_R) (\bar{\tau}_L \gamma_\mu \nu_L) + C_{S_L} (\bar{c}_R b_L) (\bar{\tau}_R \nu_L) + C_{S_R} (\bar{c}_L b_R) (\bar{\tau}_R \nu_L) + C_T (\bar{c}_R \sigma_{\mu\nu} b_L) (\bar{\tau}_R \sigma^{\mu\nu} \nu_L) \right] + \text{h.c.}$$

## SMEFT-LEFT Matching:

$$\text{SM } C_{V_L} = -v^2 \sum_i \frac{V_{2i}}{V_{23}} [\mathcal{C}_{lq}^{(3)}]_{33i3},$$

$$C_{V_R} = \frac{v^2}{2V_{23}} [\mathcal{C}_{Hud}^{(3)}]_{23},$$

$$C_{S_L} = -\frac{v^2}{2V_{23}} [\mathcal{C}_{lequ}^{(1)}]_{3332}^*,$$

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$$C_T = -\frac{v^2}{2V_{23}} [\mathcal{C}_{lequ}^{(3)}]_{3332}^*.$$

Field	$S_1$	$R_2$	$U_1$
Quantum Numbers	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$(\mathbf{3}, \mathbf{2}, 7/6)$	$(\mathbf{3}, \mathbf{1}, 2/3)$
$[\mathcal{C}_{lq}^{(1)}]_{\alpha\beta ij}$	$\frac{1}{4} [y_1^L]_{i\alpha}^* [y_1^L]_{j\beta}$	—	$-\frac{1}{2} [x_1^L]_{i\beta} [x_1^L]_{j\alpha}^*$
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$[\mathcal{C}_{ledq}]_{\alpha\beta ij}$	—	—	$2[x_1^L]_{i\alpha}^* [x_1^R]_{j\beta}$
$[\mathcal{C}_{lequ}^{(1)}]_{\alpha\beta ij}$	$\frac{1}{2} [y_1^L]_{i\alpha}^* [y_1^R]_{j\beta}$	$-\frac{1}{2} [y_2^R]_{i\beta} [y_2^L]_{j\alpha}^*$	—
$[\mathcal{C}_{lequ}^{(3)}]_{\alpha\beta ij}$	$-\frac{1}{8} [y_1^L]_{i\alpha}^* [y_1^R]_{j\beta}$	$-\frac{1}{8} [y_2^R]_{i\beta} [y_2^L]_{j\alpha}^*$	—

Vector LQ:

$$U_1^\mu : C_{V_L}, C_{S_R}$$

Scalar LQs:

$$R_2 : C_{S_L} = 4C_T$$

$$S_1 : C_{V_L}, C_{S_L} = -4C_T$$

[L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari, F. Wilsch, [2207.10714](#)]

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$[\mathcal{C}_{lequ}^{(3)}]_{\alpha\beta ij}$	$-\frac{1}{8}[y_1^L]_{i\alpha}^*[y_1^R]_{j\beta}$	$-\frac{1}{8}[y_2^R]_{i\beta} [y_2^L]_{j\alpha}^*$	—

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[L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari, F. Wilsch, [2207.10714](#)]

# The low-energy $b \rightarrow c\tau\nu$ effective Lagrangian

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## SMEFT-LEFT Matching:

**SM**  $C_{V_L} = -v^2 \sum_i \frac{V_{2i}}{V_{23}} [\mathcal{C}_{lq}^{(3)}]_{33i3},$

$$C_{V_R} = \frac{v^2}{2V_{23}} [\mathcal{C}_{Hud}^{(3)}]_{23},$$

$$C_{S_L} = -\frac{v^2}{2V_{23}} [\mathcal{C}_{lequ}^{(1)}]_{3332}^*,$$

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$$C_T = -\frac{v^2}{2V_{23}} [\mathcal{C}_{lequ}^{(3)}]_{3332}^*.$$

Field	$S_1$	$R_2$	$U_1$
Quantum Numbers	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$(\mathbf{3}, \mathbf{2}, 7/6)$	$(\mathbf{3}, \mathbf{1}, 2/3)$
$[\mathcal{C}_{lq}^{(1)}]_{\alpha\beta ij}$	$\frac{1}{4} [y_1^L]_{i\alpha}^* [y_1^L]_{j\beta}$	—	$-\frac{1}{2} [x_1^L]_{i\beta} [x_1^L]_{j\alpha}^*$
$[\mathcal{C}_{lq}^{(3)}]_{\alpha\beta ij}$	$-\frac{1}{4} [y_1^L]_{i\alpha}^* [y_1^L]_{j\beta}$	—	$-\frac{1}{2} [x_1^L]_{i\beta} [x_1^L]_{j\alpha}^*$
$[\mathcal{C}_{ledq}]_{\alpha\beta ij}$	—	—	$2[x_1^L]_{i\alpha}^* [x_1^R]_{j\beta}$
$[\mathcal{C}_{lequ}^{(1)}]_{\alpha\beta ij}$	$\frac{1}{2} [y_1^L]_{i\alpha}^* [y_1^R]_{j\beta}$	$-\frac{1}{2} [y_2^R]_{i\beta} [y_2^L]_{j\alpha}^*$	—
$[\mathcal{C}_{lequ}^{(3)}]_{\alpha\beta ij}$	$-\frac{1}{8} [y_1^L]_{i\alpha}^* [y_1^R]_{j\beta}$	$-\frac{1}{8} [y_2^R]_{i\beta} [y_2^L]_{j\alpha}^*$	—

Vector LQ:

$$U_1^\mu : C_{V_L}, C_{S_R}$$

Scalar LQs:

$$R_2 : C_{S_L} = 4C_T$$

$$S_1 : C_{V_L}, C_{S_L} = -4C_T$$

[L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari, F. Wilsch, [2207.10714](#)]

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$[\mathcal{C}_{ledq}]_{\alpha\beta ij}$	-	-	$2[x_1^L]_{i\alpha}^*[x_1^R]_{j\beta}$
$[\mathcal{C}_{lequ}^{(1)}]_{\alpha\beta ij}$	$\frac{1}{2}[y_1^L]_{i\alpha}^*[y_1^R]_{j\beta}$	$-\frac{1}{2}[y_2^R]_{i\beta} [y_2^L]_{j\alpha}^*$	-
$[\mathcal{C}_{lequ}^{(3)}]_{\alpha\beta ij}$	$-\frac{1}{8}[y_1^L]_{i\alpha}^*[y_1^R]_{j\beta}$	$-\frac{1}{8}[y_2^R]_{i\beta} [y_2^L]_{j\alpha}^*$	-

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[L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari, F. Wilsch, [2207.10714](#)]

# Updated $S_1, R_2, U_1$ fits to data w/ following observables

- Data from low-energy  $b \rightarrow c\tau\nu$  transitions

$R_D, R_{D^*}, R_{\Lambda_c}$  [J. Aebischer, G. Isidori, M. Pesut, BAS, [2210.13422](#)]

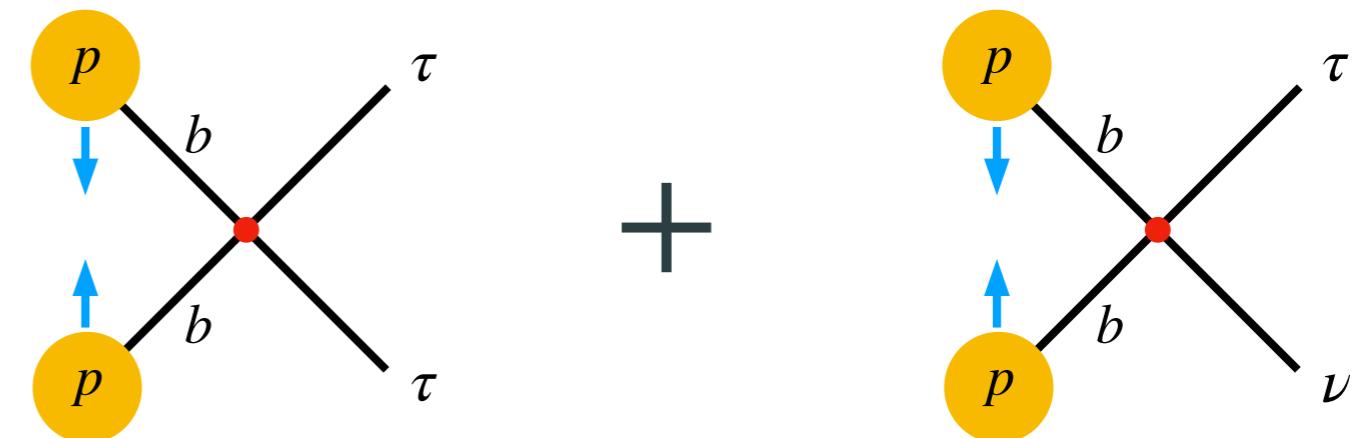
- $\tau$ -decays and EW precision observables (EWPO) [ LL running in  $y_t, g_L, g_Y$  ]

$Z + W$  pole observables + LFU tests in  $\tau$ -decays:  $g_W^\tau/g_W^\ell$

[L. Allwicher, G. Isidori, J. M. Lizana, N. Selimovic, BAS, [2302.11584](#)]

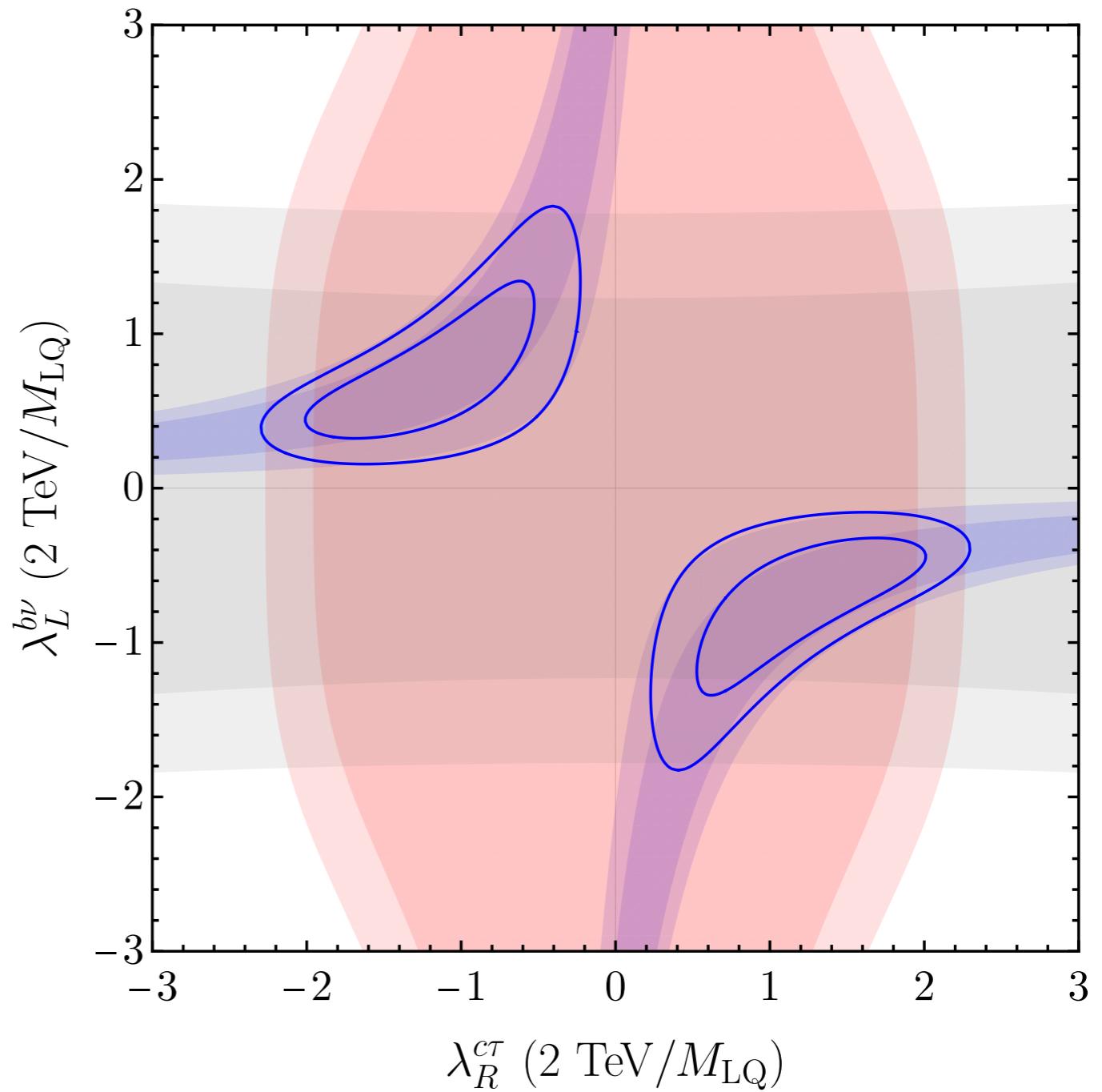
- Data from high- $p_T$  searches at the collider: di-tau  $\tau\tau$  and mono-tau  $\tau + E_T$

  
[L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari, F. Wilsch, [2207.10756](#)]



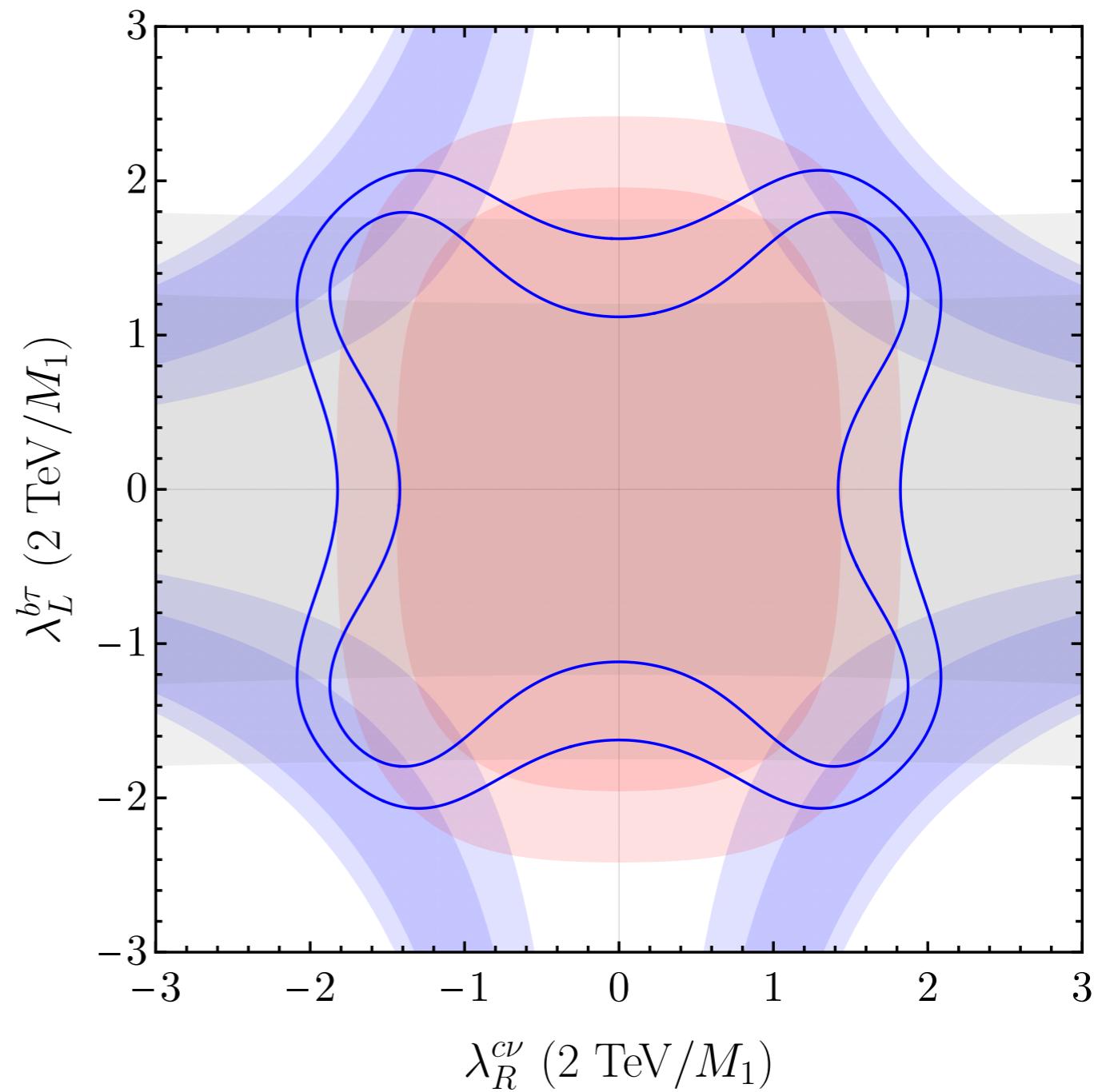
# Simplified $S_1$ scalar LQ model and fit

$$\mathcal{L} \supset \lambda_L^{b\nu} \bar{q}_L^c \epsilon \ell_L^3 S_1 + \lambda_R^{c\tau} \bar{c}_R^c \tau_R S_1$$



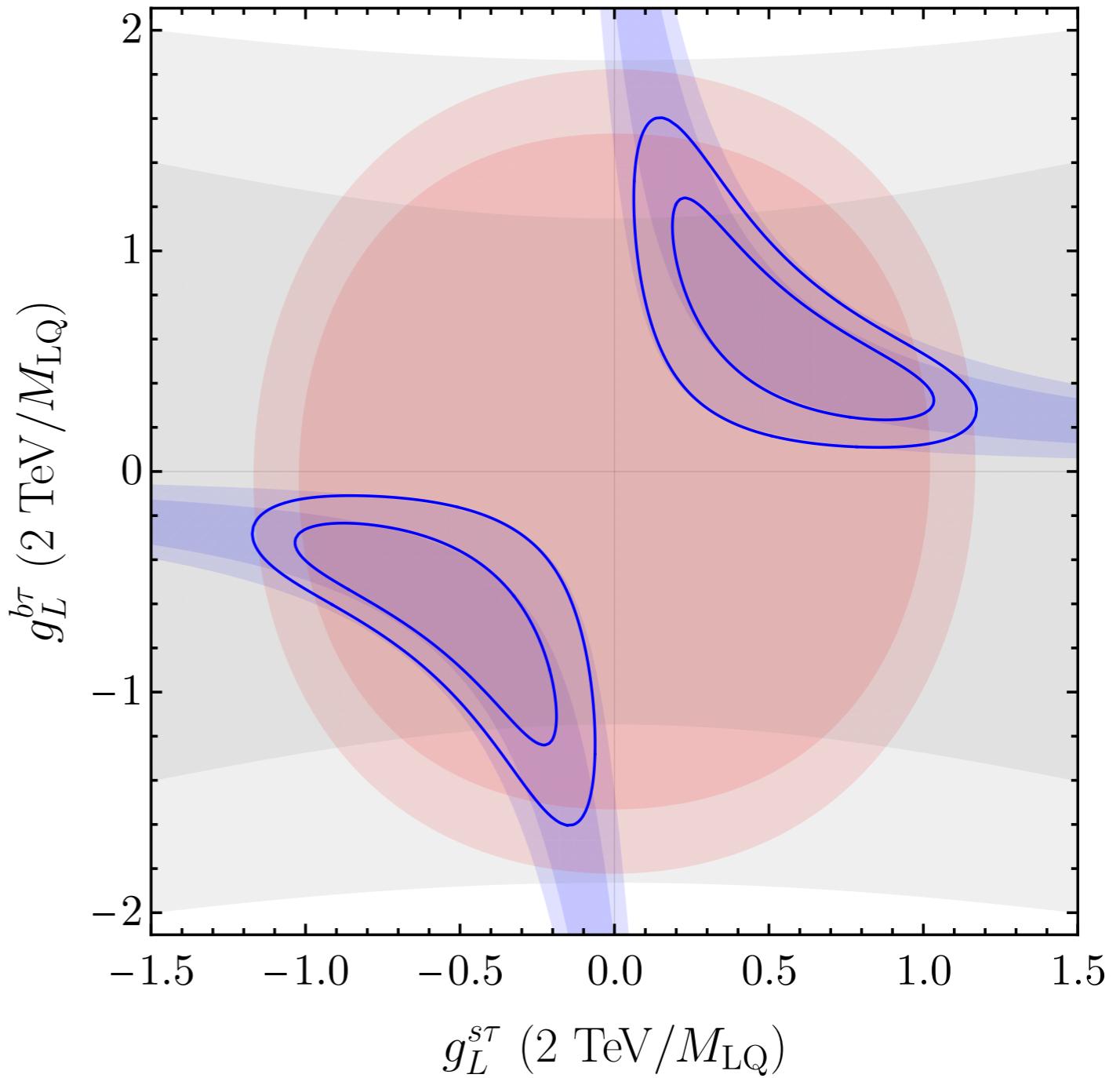
# Simplified $R_2$ scalar LQ model and fit

$$\mathcal{L} \supset \lambda_L^{b\tau} \bar{q}_L^3 R_2 \tau_R - \lambda_R^{c\nu} \bar{c}_R R_2 \epsilon \ell_L^3$$

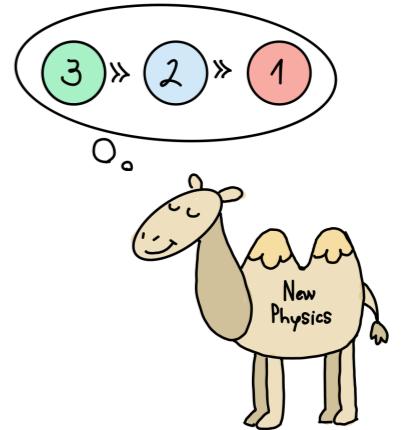


# Simplified $U_1$ vector LQ model and fit

$$\mathcal{L} \supset \left( g_L^{b\tau} \bar{q}_L^3 \gamma_\mu \ell_L^3 + g_L^{s\tau} \bar{q}_L^2 \gamma_\mu \ell_L^3 \right) U_1^\mu$$

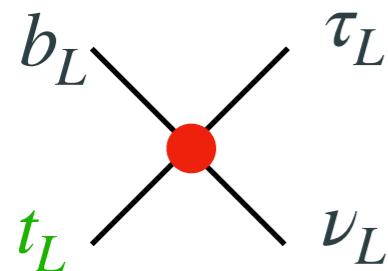


# U(2)-like new physics in $b \rightarrow c\tau\nu$ decays



- Actually, following the U(2) hypothesis, we should have:

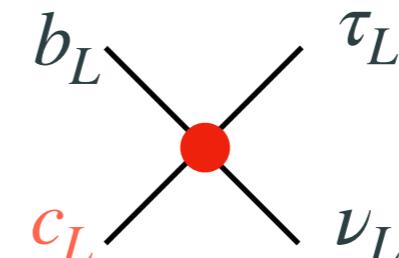
**Flavor conserving**



$$\mathcal{A}_{\text{NP}}^{33} \sim \frac{1}{\Lambda_{\text{NP}}^2}$$

+

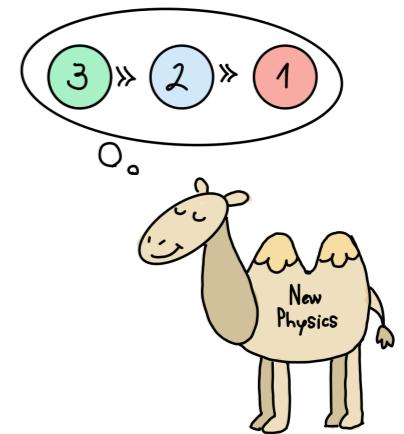
**Flavor violating**



$$\mathcal{A}_{\text{NP}}^{23} \sim \frac{V_q}{\Lambda_{\text{NP}}^2}$$

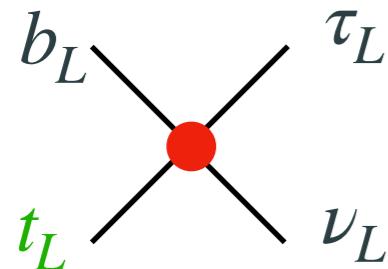
$$\mathcal{A}_{\text{NP}}(b \rightarrow c\tau\nu) = V_{cb}\mathcal{A}_{\text{NP}}^{33} + V_{cs}\mathcal{A}_{\text{NP}}^{23}$$

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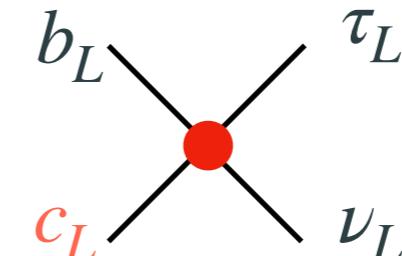
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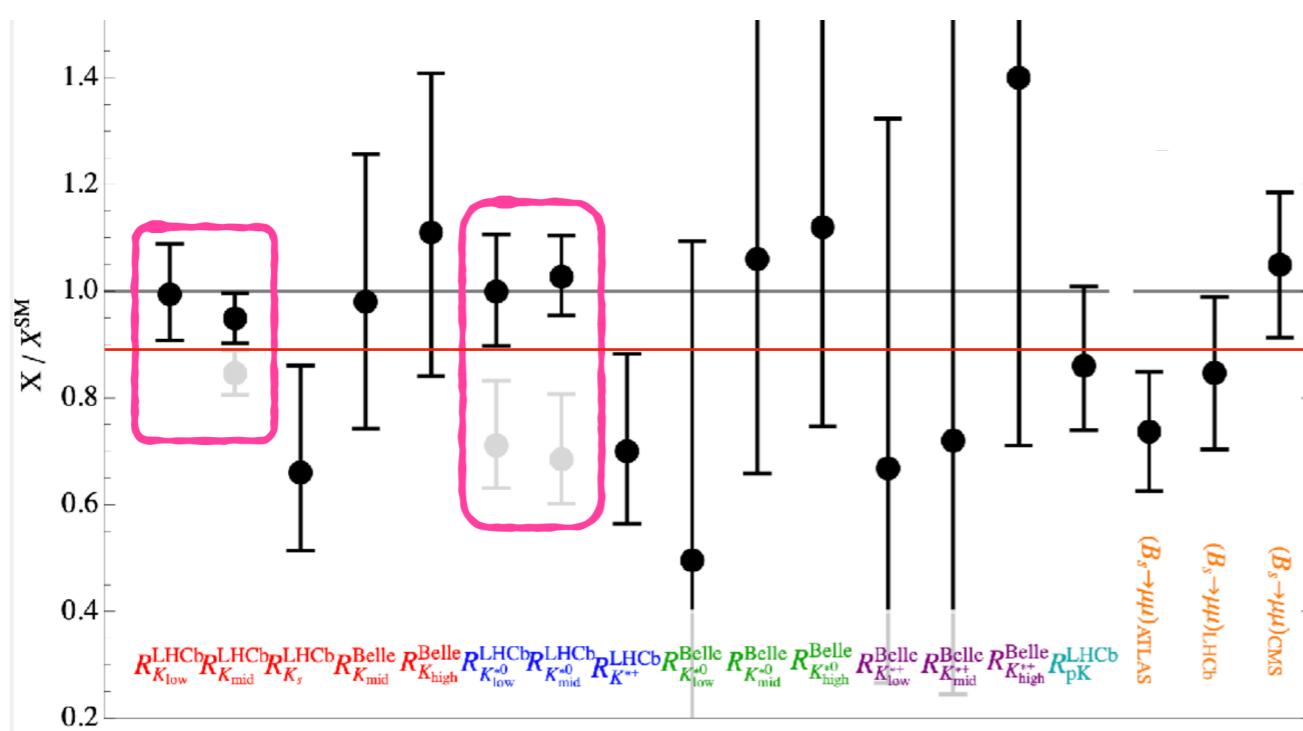
- U(2) suppressed flavor violation means we need an even lower NP scale!

$$2 \frac{\mathcal{A}_{\text{NP}}}{\mathcal{A}_{\text{SM}}} \approx \frac{v^2}{\Lambda_{\text{NP}}^2} \left( 1 + \frac{V_q}{V_{cb}} \right) \approx \delta R_{D^*} \quad \Rightarrow \quad \Lambda_{\text{NP}} \approx 1.3 \text{ TeV} \left( \frac{0.12}{\delta R_{D^*}} \right)^{1/2}$$

$(V_q = 0.1)$

# A final comment on $R_{K^{(*)}}$

- 12/2022: a second LHCb analysis of  $R_K$  &  $R_{K^*}$  establishes  $\mu/e$  lepton flavor universality in  $b \rightarrow sll$  at  $\sim 5\%$  level [LHCb,221209152]



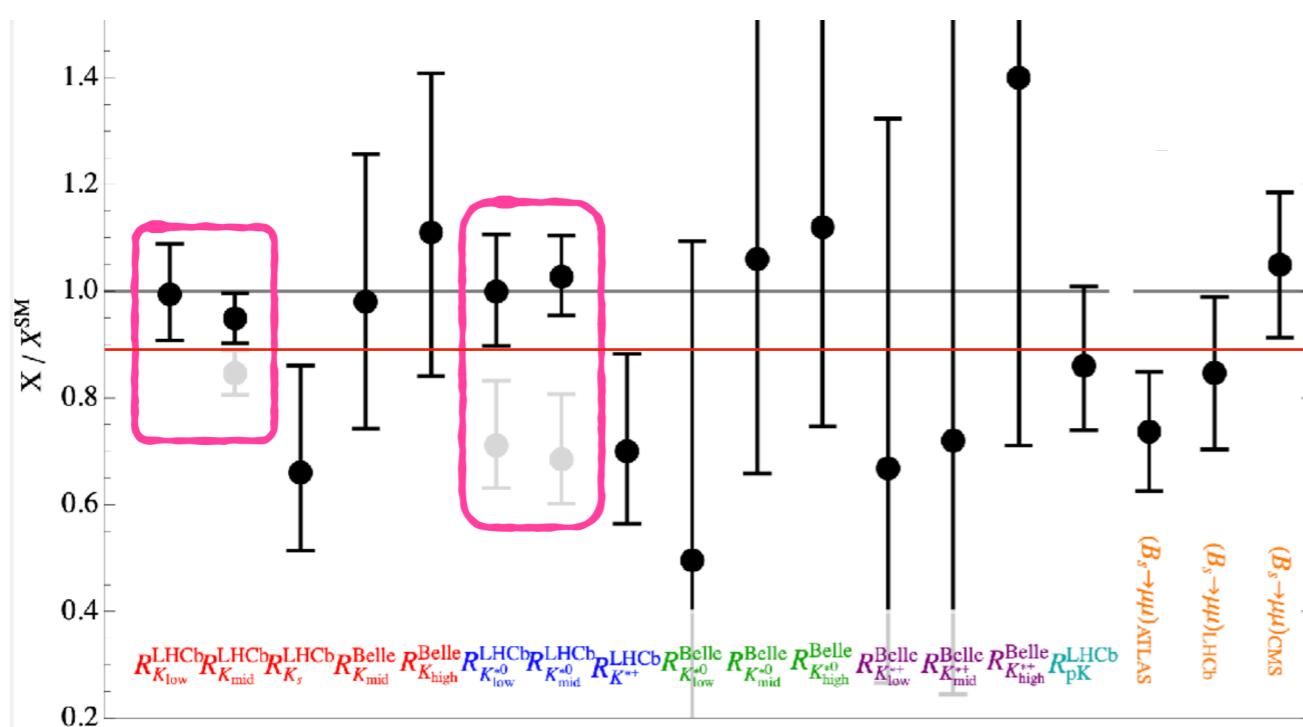
[compilation of  $b \rightarrow s\mu\mu$  clean observables  
as of Dec. 2022 (©David Marzocca)]

$$\begin{aligned} \text{low-}q^2 & \left\{ \begin{array}{l} R_K = 0.994^{+0.090}_{-0.082} \text{ (stat)}^{+0.029}_{-0.027} \text{ (syst)}, \\ R_{K^*} = 0.927^{+0.093}_{-0.087} \text{ (stat)}^{+0.036}_{-0.035} \text{ (syst)}, \end{array} \right. \\ \text{central-}q^2 & \left\{ \begin{array}{l} R_K = 0.949^{+0.042}_{-0.041} \text{ (stat)}^{+0.022}_{-0.022} \text{ (syst)}, \\ R_{K^*} = 1.027^{+0.072}_{-0.068} \text{ (stat)}^{+0.027}_{-0.026} \text{ (syst)}. \end{array} \right. \end{aligned}$$

- Still room for small  $\mu/e$  lepton flavor violation at the  $\sim 10\%$  level

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- Still room for small  $\mu/e$  lepton flavor violation at the  $\sim 10\%$  level

$U(2)$ -breaking parameter:

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[ (\bar{q}_L^3 \gamma_\mu \ell_L^3) + \beta_L^{s\tau} (\bar{q}_L^2 \gamma_\mu \ell_L^3) + \beta_L^{b\mu} (\bar{q}_L^3 \gamma_\mu \ell_L^2) + \beta_L^{s\mu} (\bar{q}_L^2 \gamma_\mu \ell_L^2) \right]$$

Nothing changes here,  
still calls for light NP!

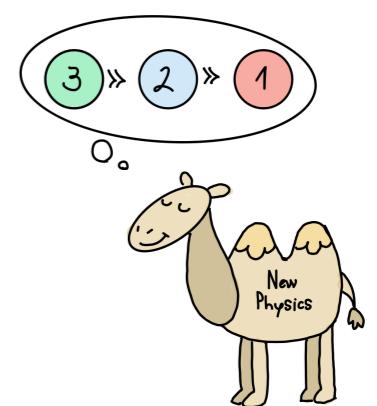
$R_{D^{(*)}}$

$V_\ell$

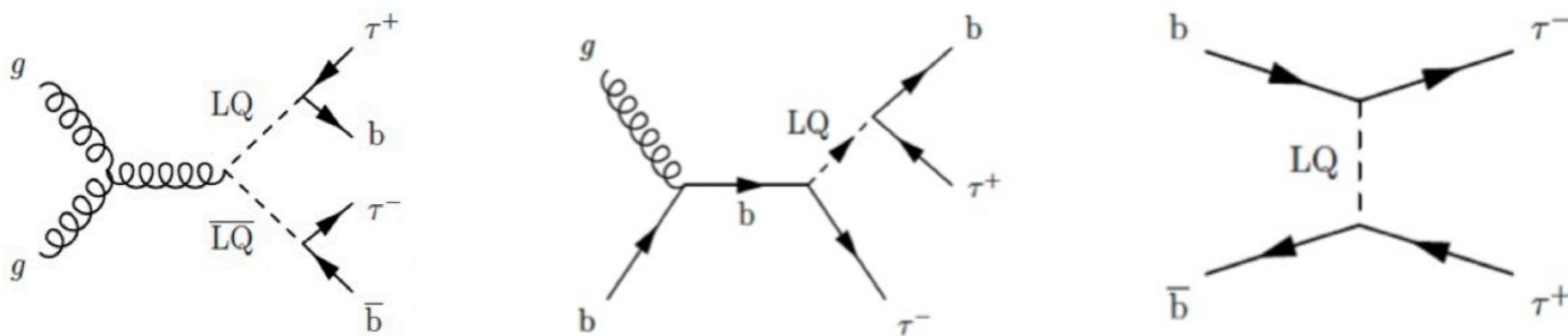
$V_q V_\ell$

$U(2)_\ell$  breaking  $V_\ell$  is  
simply smaller now.

$R_{K^{(*)}}$

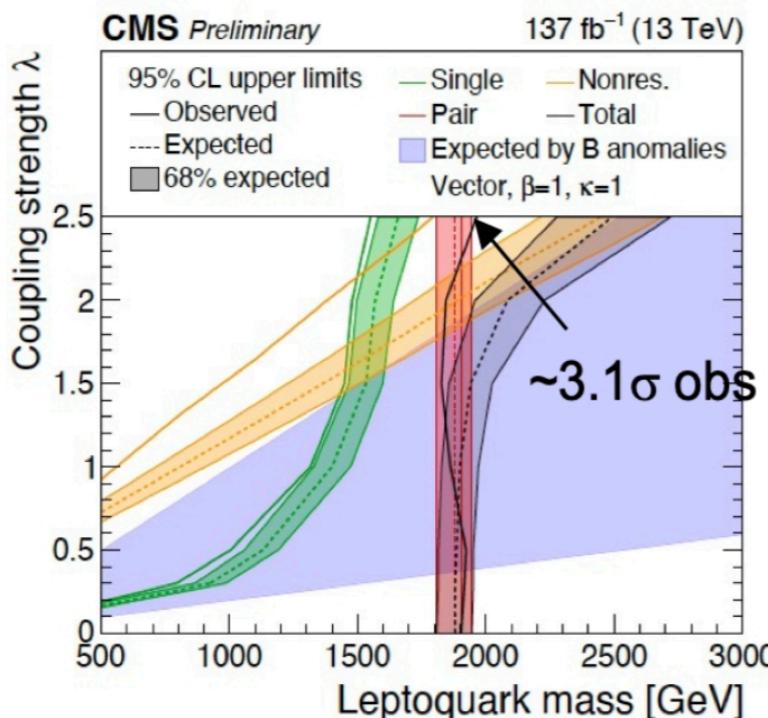


# High-energy searches: $U_1$ leptoquark

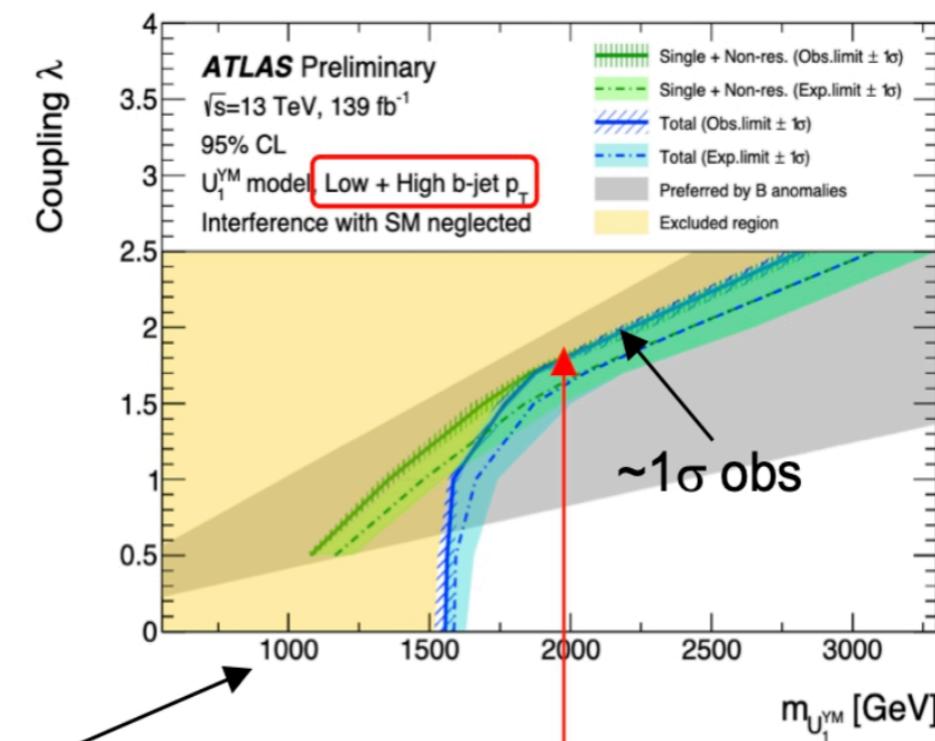


**Caveat:** BR=1 (CMS) vs BR=0.5 (ATLAS)

[CMS-PAS-EXO-19-016](#)



[EXOT-2022-39](#)

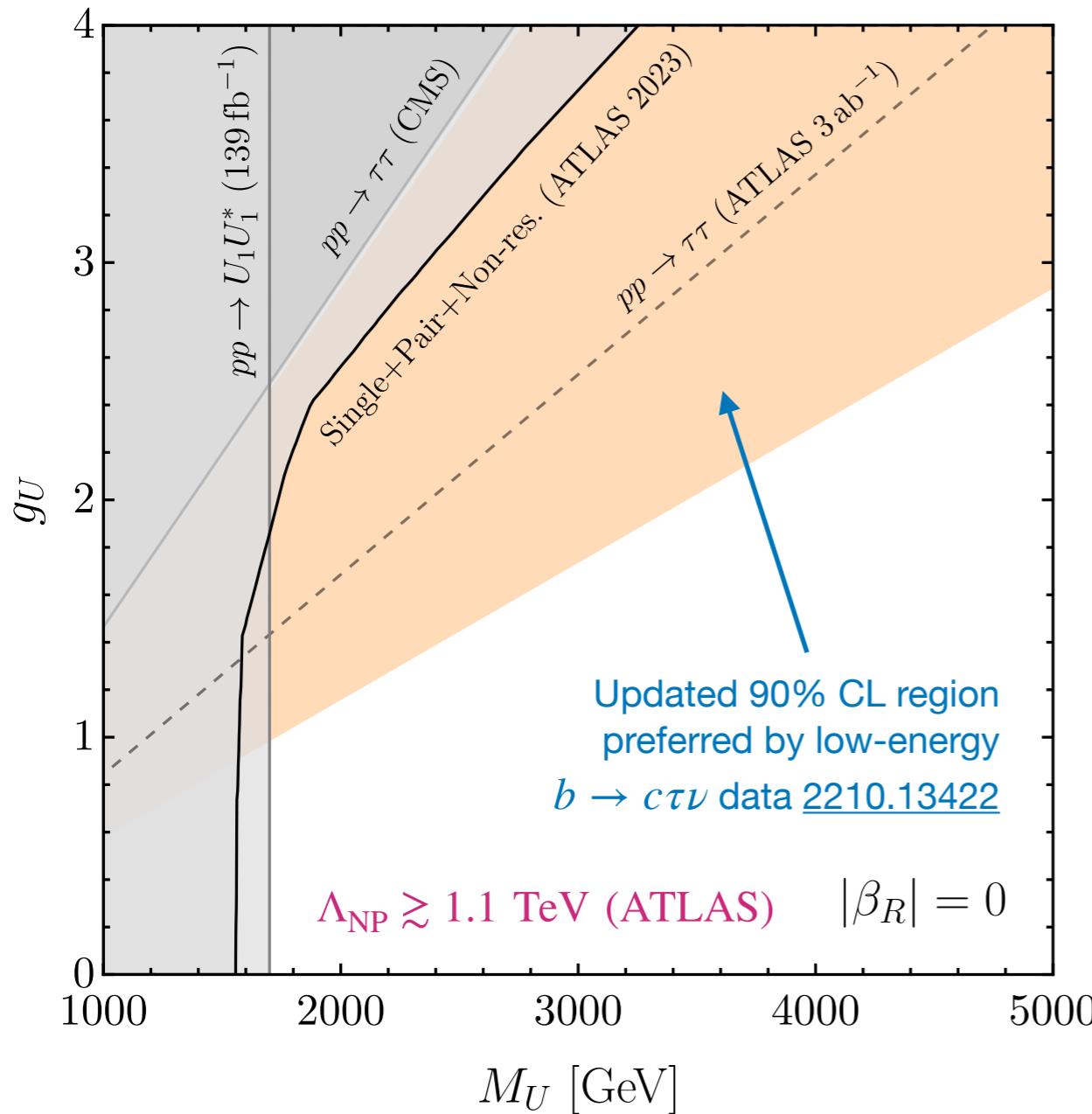


Large improvement in sensitivity  
when adding low b-jet  $p_T$  category

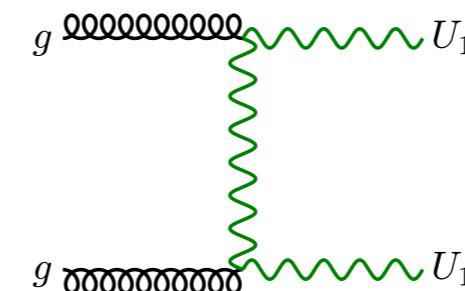
**Excludes  
CMS' excess**

# High-energy searches: $U_1$ leptoquark model (LH)

- The LHC is already probing the preferred region for the  $U_1$  leptoquark model! CMS has a  $3\sigma$  excess, ATLAS just set weaker than expected limits.....too soon to say.



$U_1$  pair production



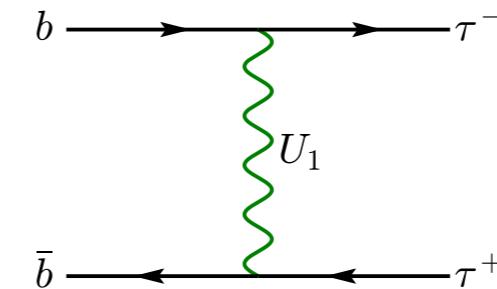
$$U_1 \rightarrow b\tau^+, t\bar{\nu}$$

$$\mathcal{B}(U_1 \rightarrow b\tau^+) \approx 0.5$$



2012.0417

Drell-Yan t-channel exchange:  $\tau\tau$



2002.1222

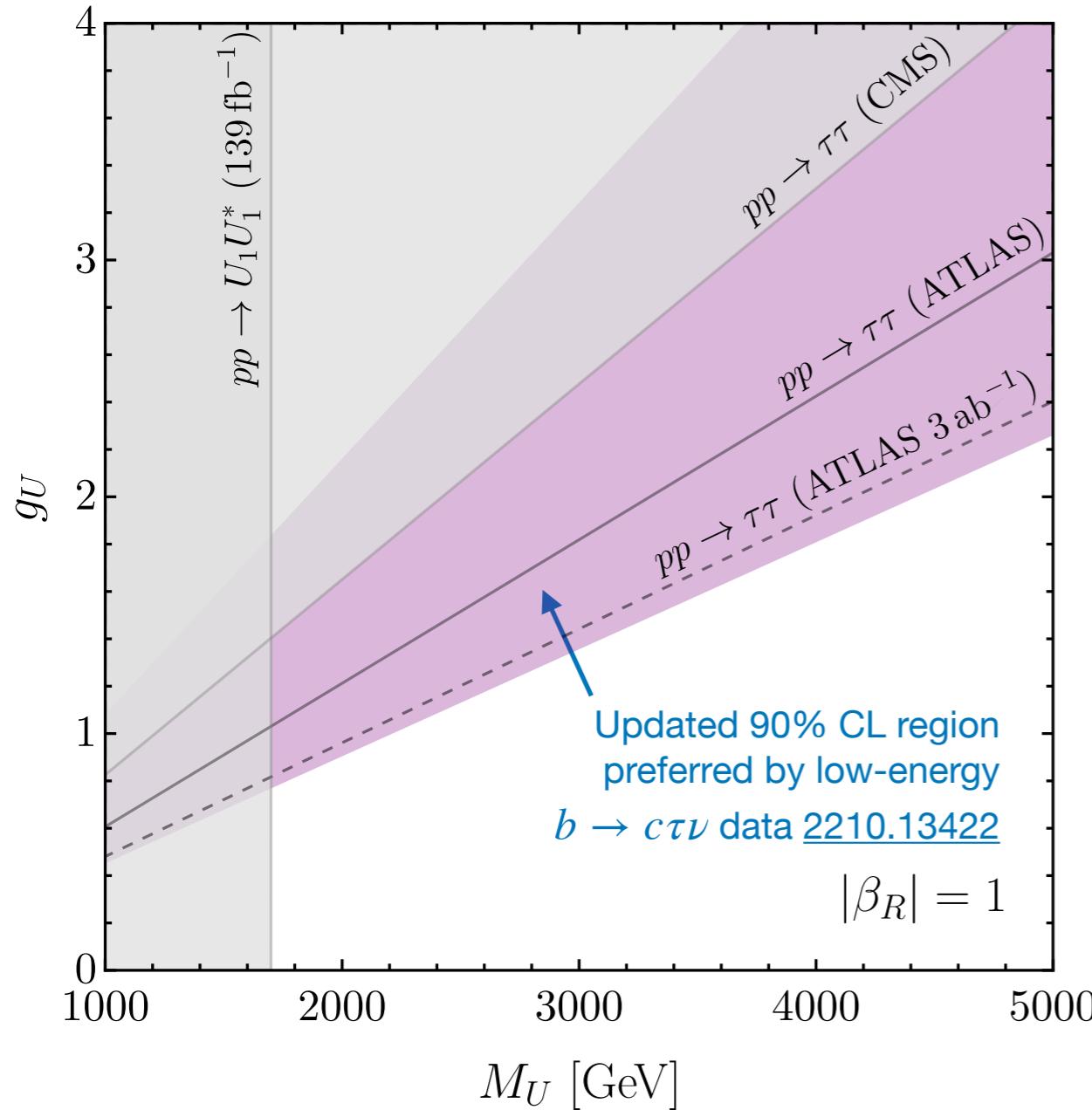
High mass Drell-Yan tails

QCD corrections: [U. Haisch, L. Schnell, S. Schulte, [2209.12780](#)]

[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, [2210.13422](#)]

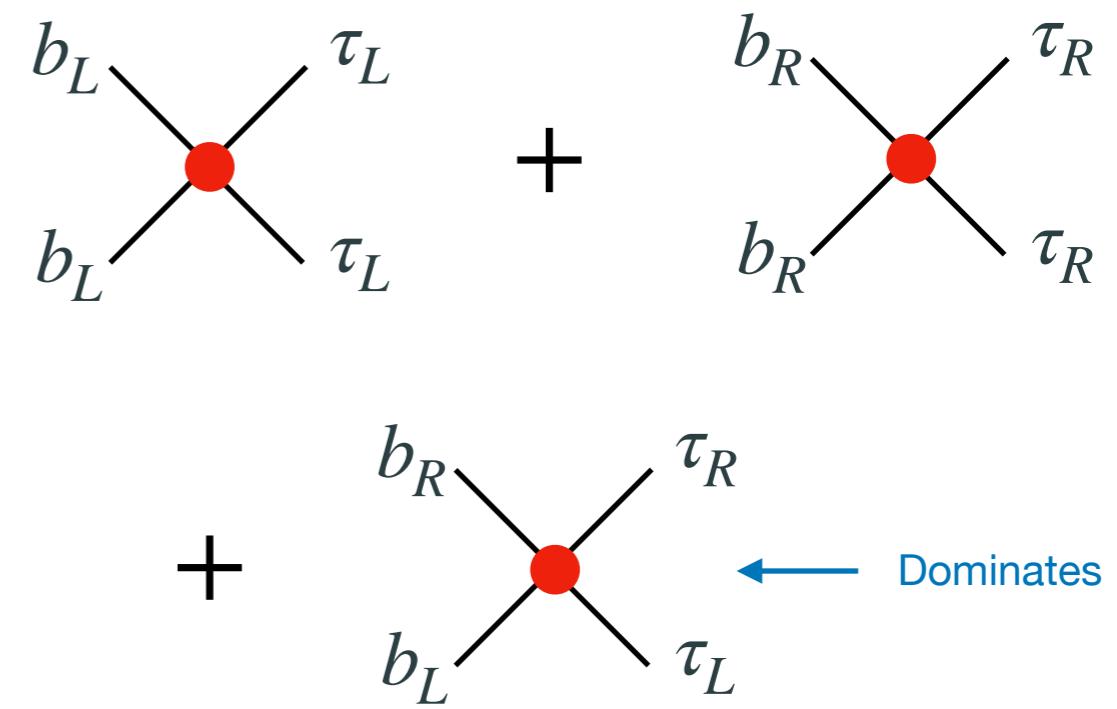
# High-energy searches: $U_1$ leptoquark model (L&R)

- $U_1$  leptoquark model w/ RH currents preferred region fully **within the HL-LHC reach!**



$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[ (\bar{q}_L^3 \gamma_\mu \ell_L^3) + \beta_R^{b\tau} (\bar{b}_R \gamma_\mu \tau_R) \right] \quad (\beta_R^{b\tau} = -1)$$

- Additional contributions give stronger bound from t-channel Drell-Yan  $\tau\tau$ :



[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, [2210.13422](https://arxiv.org/abs/2210.13422)]

# The low-energy $b \rightarrow c\tau\nu$ effective Lagrangian

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Field	$S_1$	$R_2$	$U_1$
Quantum Numbers	( $\bar{\mathbf{3}}, \mathbf{1}, 1/3$ )	( $\mathbf{3}, \mathbf{2}, 7/6$ )	( $\mathbf{3}, \mathbf{1}, 2/3$ )
$[\mathcal{C}_{ledq}]_{\alpha\beta ij}$	—	—	$2[x_1^L]_{i\alpha}^* [x_1^R]_{j\beta}$
$[\mathcal{C}_{lequ}^{(1)}]_{\alpha\beta ij}$	$\frac{1}{2}[y_1^L]_{i\alpha}^* [y_1^R]_{j\beta}$	$-\frac{1}{2}[y_2^R]_{i\beta} [y_2^L]_{j\alpha}^*$	—
$[\mathcal{C}_{lequ}^{(3)}]_{\alpha\beta ij}$	$-\frac{1}{8}[y_1^L]_{i\alpha}^* [y_1^R]_{j\beta}$	$-\frac{1}{8}[y_2^R]_{i\beta} [y_2^L]_{j\alpha}^*$	—
$[\mathcal{C}_{eu}]_{\alpha\beta ij}$	$\frac{1}{2}[y_1^R]_{j\beta} [y_1^R]_{i\alpha}^*$	—	—
$[\mathcal{C}_{ed}]_{\alpha\beta ij}$	—	—	$-[x_1^R]_{i\beta} [x_1^R]_{j\alpha}^*$
$[\mathcal{C}_{\ell u}]_{\alpha\beta ij}$	—	$-\frac{1}{2}[y_2^L]_{i\beta} [y_2^L]_{j\alpha}^*$	—
$[\mathcal{C}_{qe}]_{ij\alpha\beta}$	—	$-\frac{1}{2}[y_2^R]_{i\beta} [y_2^R]_{j\alpha}^*$	—
$[\mathcal{C}_{lq}^{(1)}]_{\alpha\beta ij}$	$\frac{1}{4}[y_1^L]_{i\alpha}^* [y_1^L]_{j\beta}$	—	$-\frac{1}{2}[x_1^L]_{i\beta} [x_1^L]_{j\alpha}^*$
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[L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari, F. Wilsch, [2207.10756](#)]