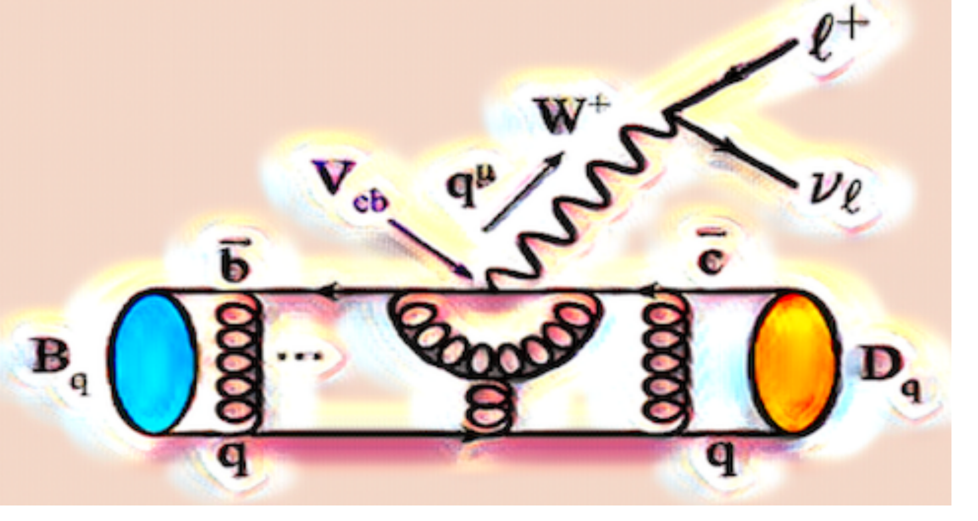
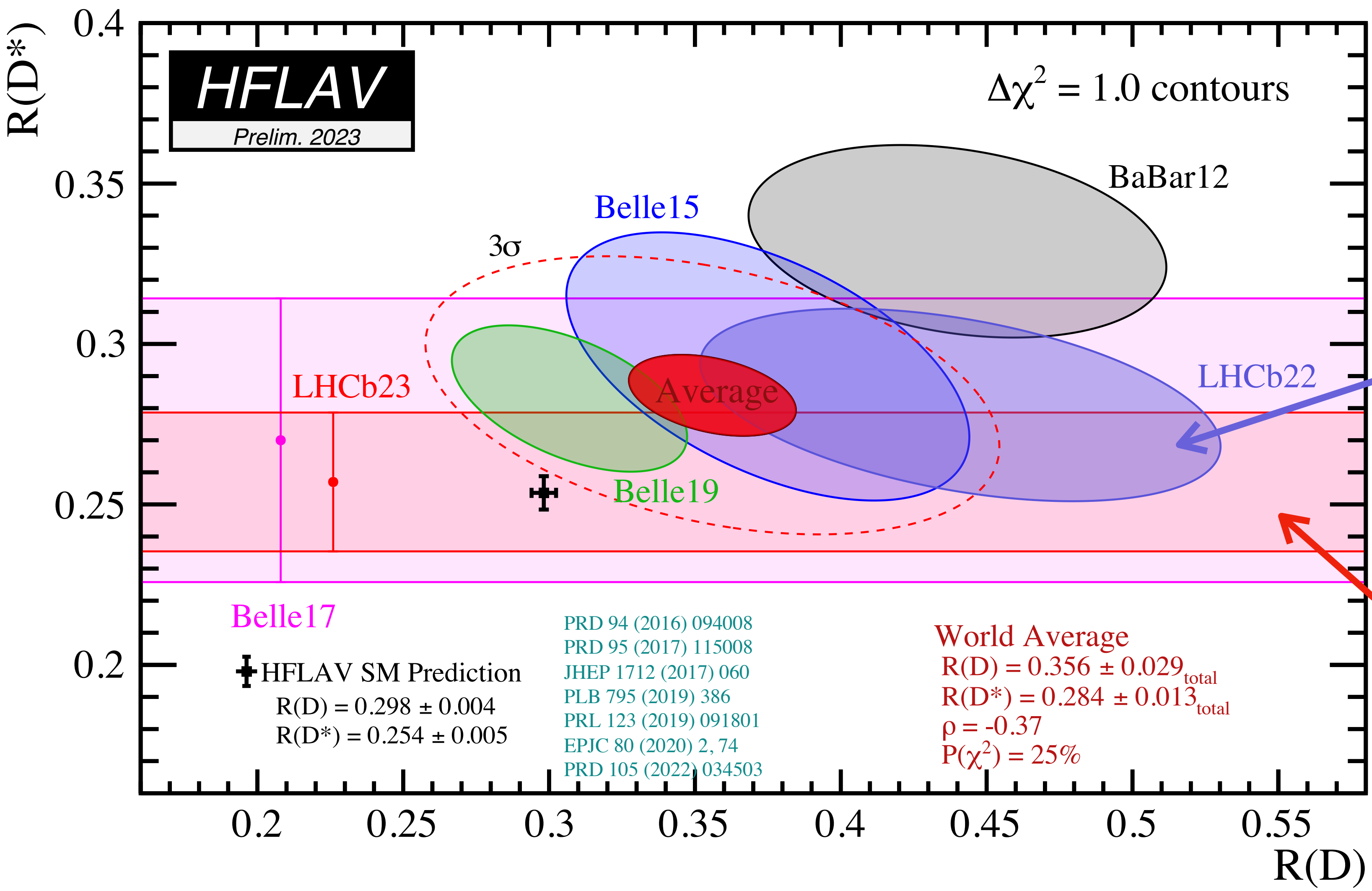
Mostly Leptoquarks and some VL Fermions

Ben A. Stefanek
Physik-Institut
University of Zurich



11th Edition of the LHC-Physics Conference
Metropol Palace, Belgrade, Serbia
May 23rd, 2023

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



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

$$[\ell = e, \mu]$$

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

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

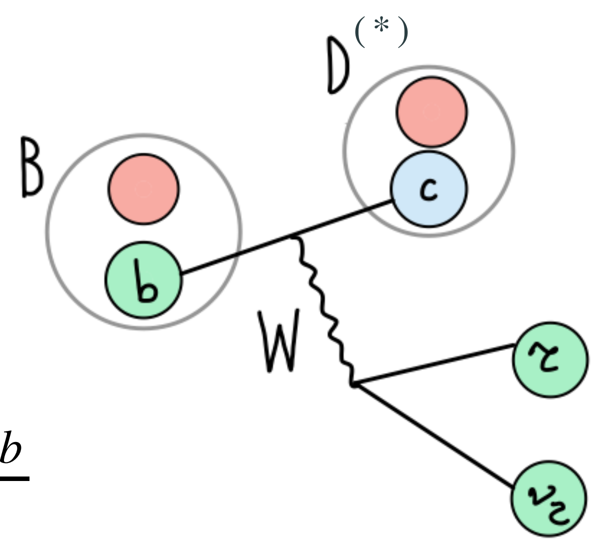
- Theoretically semi-clean. Measurements by Babar, Belle, LHCb in good agreement.
- Enhancement of $\sim 10\,\%$ over SM due to excess in tau mode: $B \to D^{(*)}\tau\bar{\nu}_\tau$.
- Combined, $3.2\,\sigma$ **tension** w.r.t SM. Measurement of $R_{\Lambda_c}/R_{\Lambda_c}^{\text{SM}} = 0.73 \pm 0.23$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

New physics in $b \to c\tau\nu$ decays

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

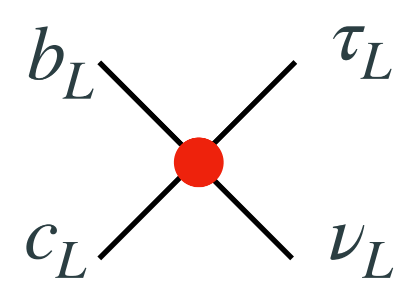
- We need ~10% of a tree-level SM process due to NP. Heavy NP should therefore also be tree-level to compete. Consider Fermi-like LH NP:

<u>SM process</u>



$$\mathcal{A}_{SM} \sim \frac{g_L^2 V_{cb}}{2M_W^2} = \frac{2V_{cb}}{v^2}$$

<u>Heavy new physics</u>

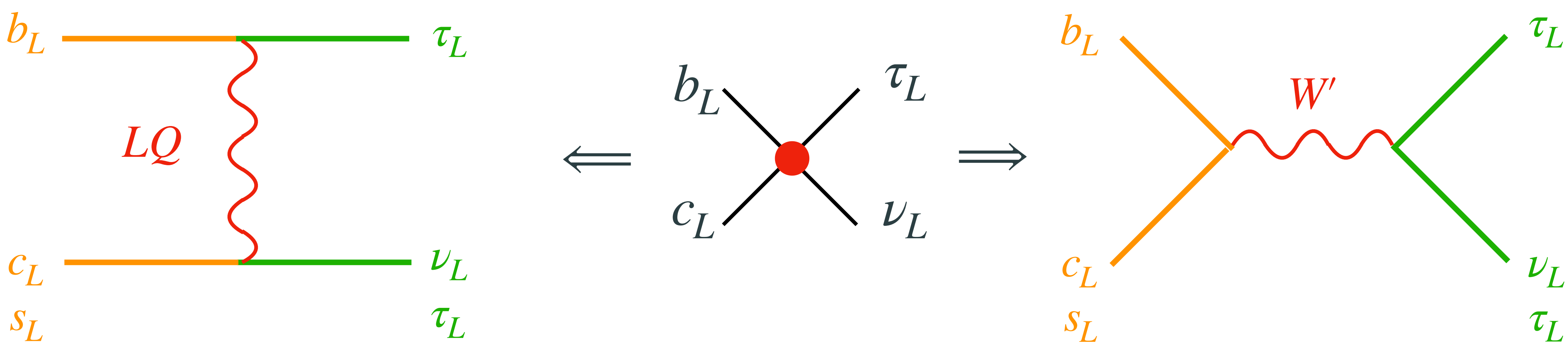


$$\mathcal{A}_{NP} \sim \frac{1}{\Lambda_{NP}^2}$$

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

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

What kind of new particles could we have?

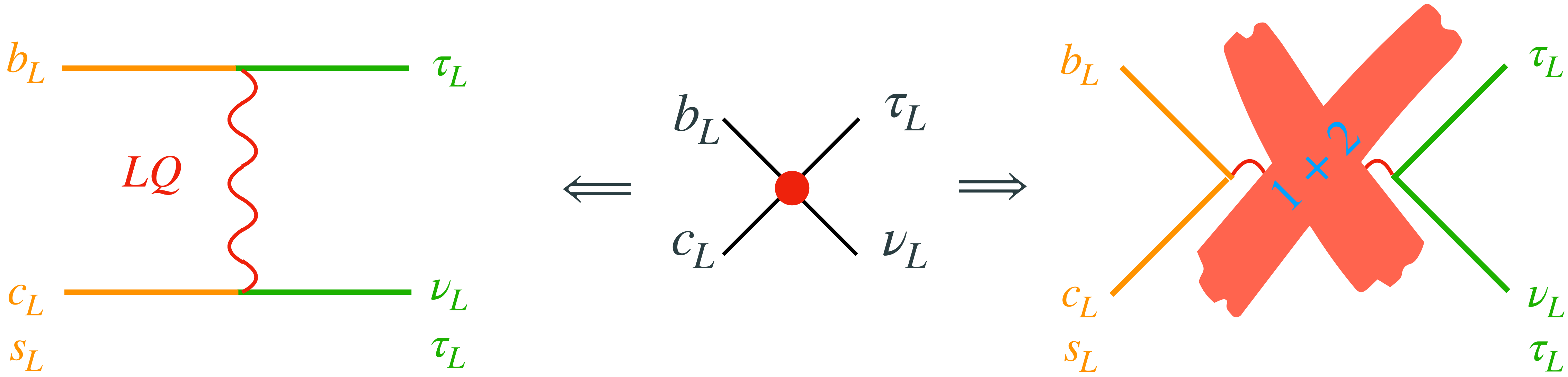


- LH NP $\Longrightarrow$ $b \to s\tau\tau(\nu\nu)$ couplings. LQ's have two important advantages

1. $\Delta F = 2:$

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

Only leptoquarks are viable mediators!



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

1. $\Delta F = 2$:

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

Shopping for Leptoquarks

- There are three viable options on the leptoquark market:

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

[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]

Which Leptoquark?

- There are three viable options on the leptoquark market:

  Vector Leptoquarks:

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

  Scalar Leptoquarks:

  ★ $S_1 \sim (\bar{3},1,1/3)$ $R_2 \sim (3,2,7/6)$

Which Leptoquark?

- There are three viable options on the leptoquark market:

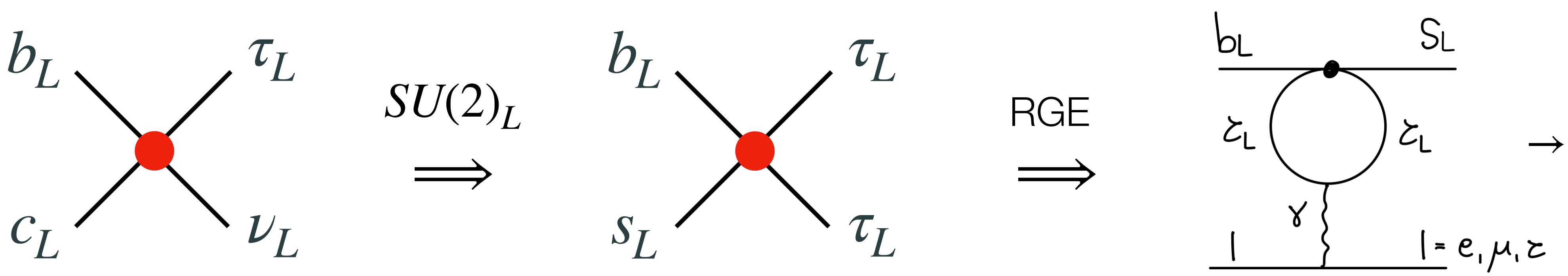
Vector Leptoquarks:

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

Scalar Leptoquarks:

★ $S_1 \sim (\bar{3},1,1/3)$ $R_2 \sim (3,2,7/6)$

- Only the U_1 vector LQ also gives a *flavor universal* effect in $b \to s\ell\ell$ via RGE:



$\to \Delta C_9^U = C_9^U - C_9^{\rm SM}$

"Dirty" $b \to s\ell^+\ell^-$ anomalies prefer: $\Delta C_9^U \approx -0.75 \pm 0.25$

Simplified model for U_1 leptoquark

$U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$

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

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

Simplified model for U_1 leptoquark

$U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$

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

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

RUNNING to EW SCALE + MATCHING

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

Simplified model for U_1 leptoquark

$U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$

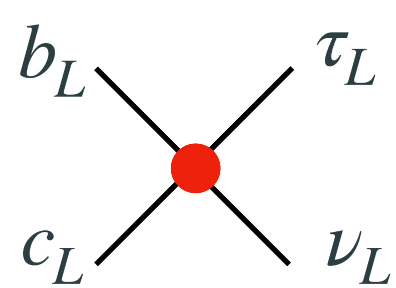
$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[(\bar{q}_L^3 \gamma_\mu \ell_L^3) + \beta_L^{s\tau} (\bar{q}_L^2 \gamma_\mu \ell_L^3) + \beta_R^{b\tau} (\bar{b}_R \gamma_\mu \tau_R) \right] + \mathrm{h.c.}$$

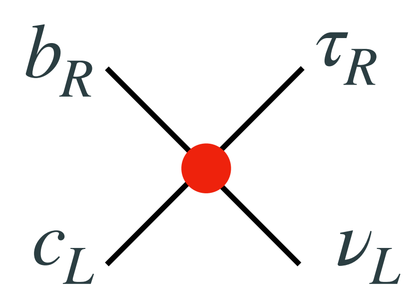
Integrate out the U_1 LQ: $\dfrac{1}{\Lambda_{\mathrm{NP}}^2} = \dfrac{g_U^2}{2M_U^2}$

RUNNING to EW SCALE + MATCHING

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

Contact interaction:





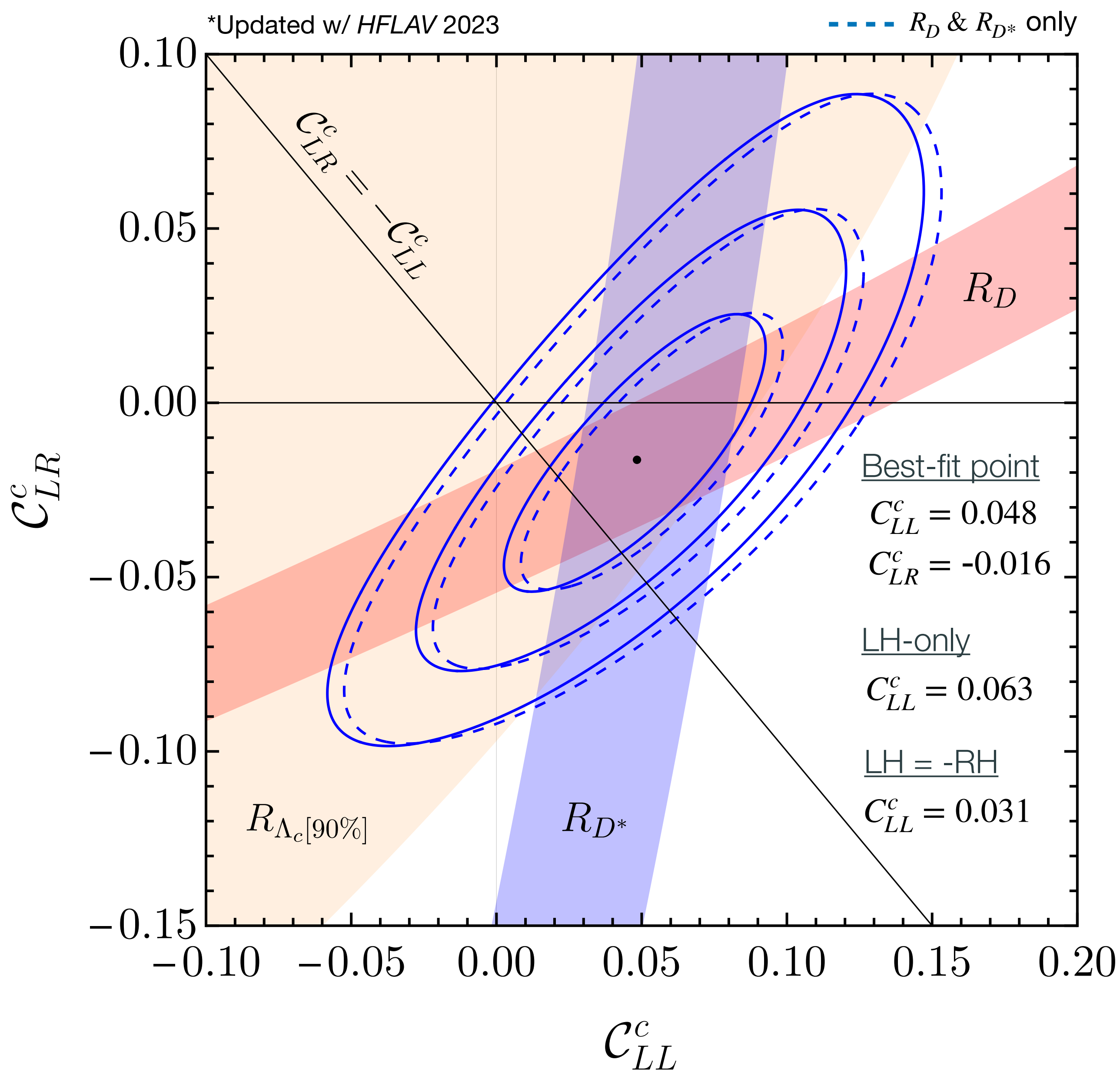
Low-energy WC's ↔ Model parameters:

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

Low-energy fit for U_1 leptoquark model

$U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$

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



$$\delta R_{D^{(*)}} \approx 2C^c_{LL} - a_{D^{(*)}} C^c_{LR} \qquad \begin{cases} a_D \approx 3.00 \\ a_{D^*} \approx 0.24 \end{cases}$$

Low-energy WC's ↔ Model parameters

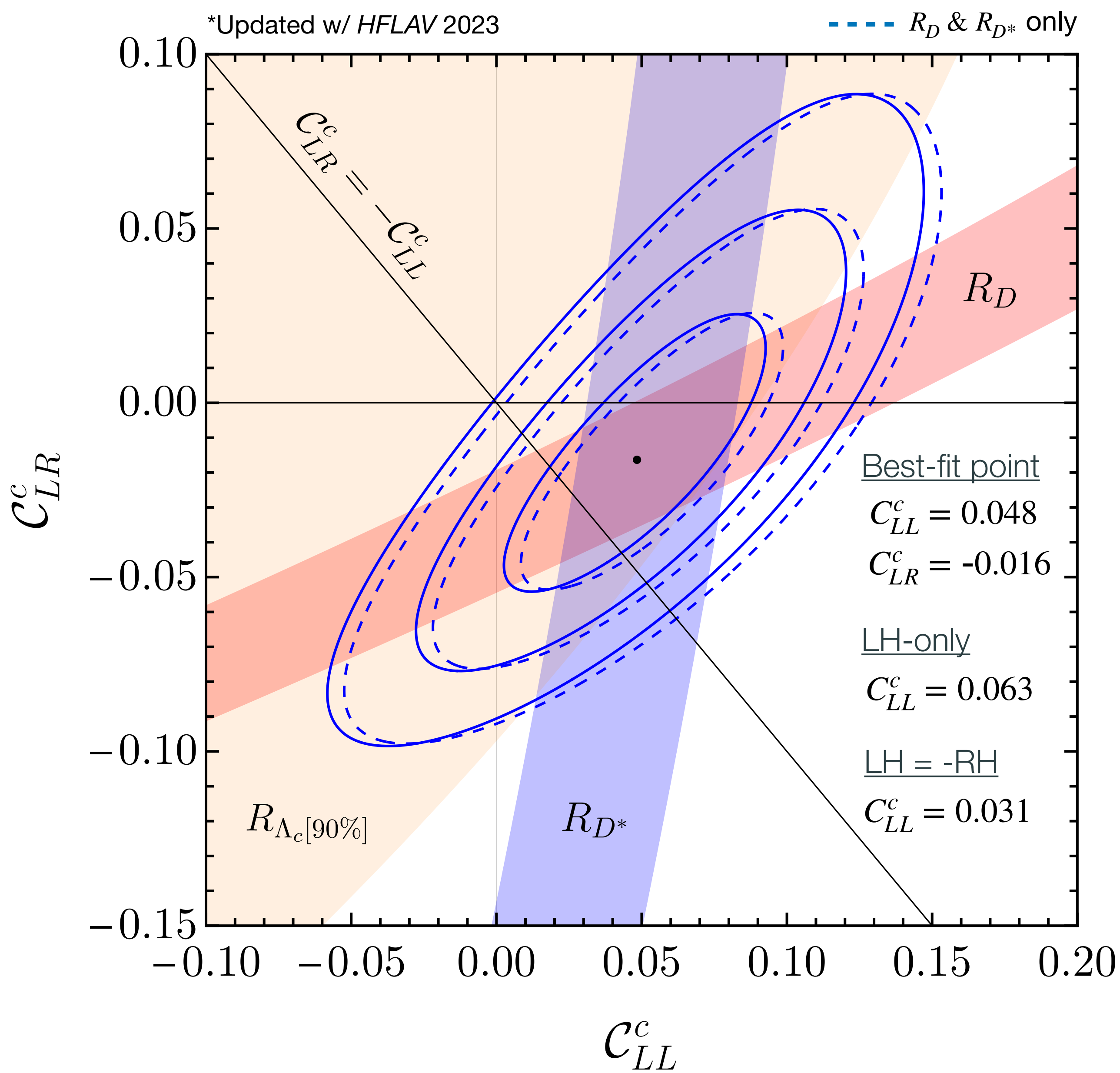
$$C^c_{LL} = \frac{g_U^2 v^2}{4M_U^2}\left(1 + \frac{V_{cs}}{V_{cb}} \beta_L^{s\tau}\right), \qquad C^c_{LR} = \beta_R^{b\tau*} C^c_{LL}$$

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

Low-energy fit for U_1 leptoquark model

$U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$

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



$$\delta R_{D^{(*)}} \approx 2C^c_{LL} - a_{D^{(*)}} C^c_{LR} \qquad \begin{cases} a_D \approx 3.00 \\ a_{D^*} \approx 0.24 \end{cases}$$

Low-energy WC's ↔ Model parameters

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

Matching: NP scale and U(2)-breaking

$$\frac{1}{\Lambda^2_{\rm NP}} = \frac{g_U^2}{2M_U^2}, \qquad V_q = \beta_L^{s\tau}$$

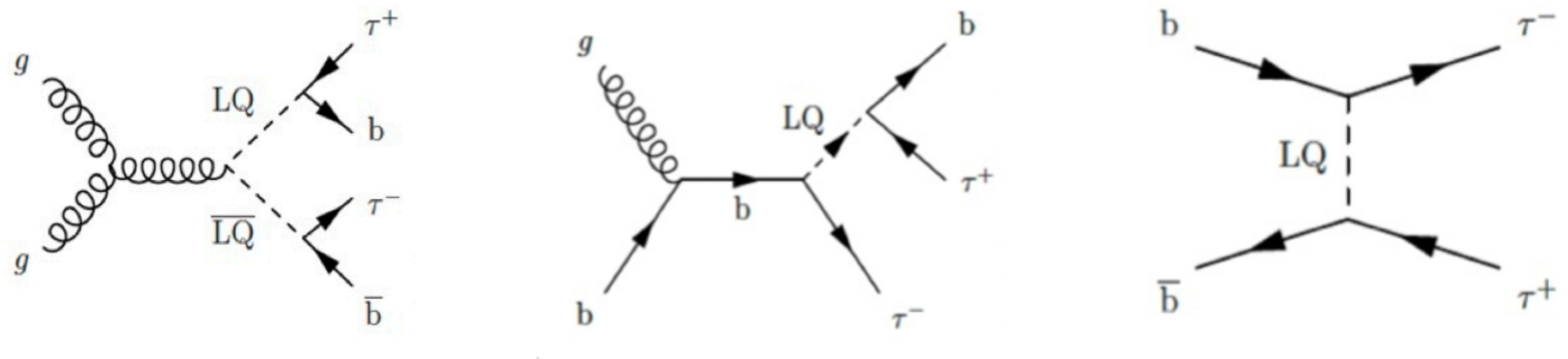
New physics scale preferred by low-energy fit:

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

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

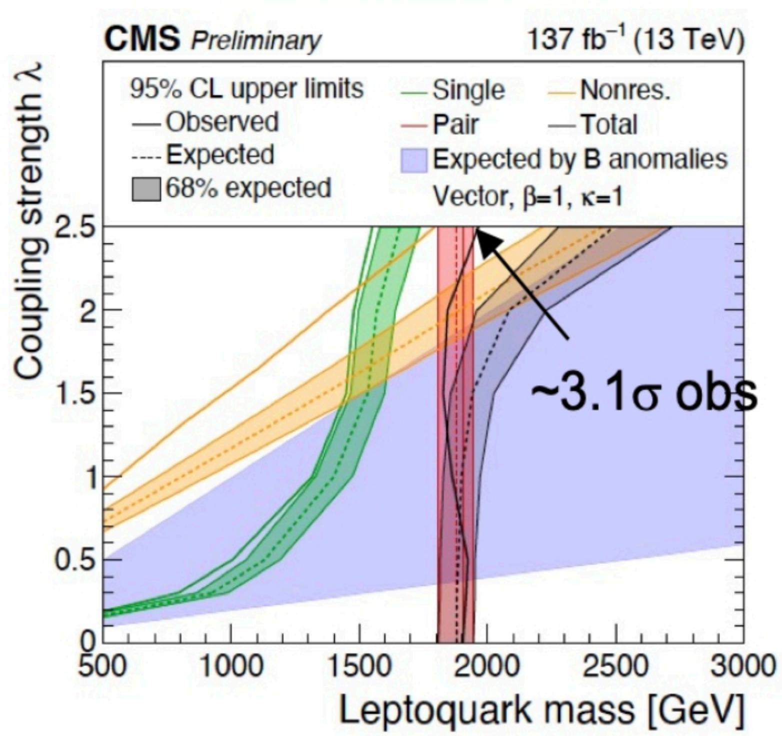
[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, 2210.13422]

High-energy searches: U_1 leptoquark

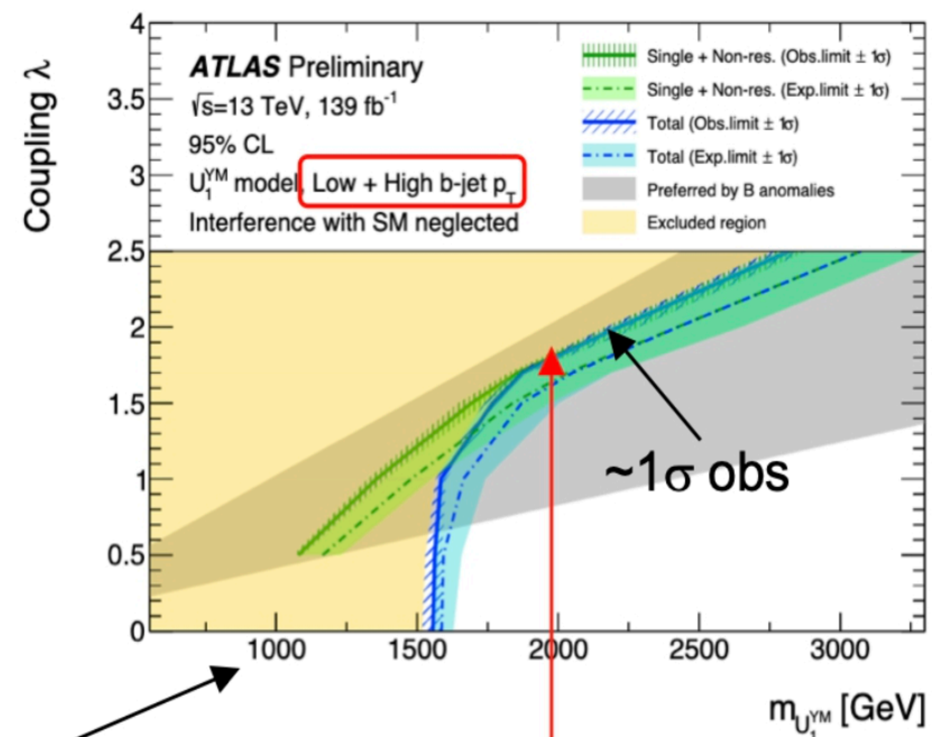


Caveat: BR=1 (CMS) vs BR=0.5 (ATLAS)

CMS-PAS-EXO-19-016



EXOT-2022-39



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

Excludes CMS' excess

[A. Juste, Moriond EW '23]

UV Completion for the U_1 Leptoquark

UV Model: New flavor non-universal gauge interactions

Based on "4321" gauge symmetry:

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

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

UV Model: New flavor non-universal gauge interactions

Based on "4321" gauge symmetry:

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

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

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

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

- 3rd family charged under $SU(4)_h$
  $\Longrightarrow$ 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)

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

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]

UV Model: The origin of light-heavy CKM mixing

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

$$\psi_L \sim \begin{pmatrix} q_L^3 \\ \ell_L^3 \end{pmatrix} \qquad \psi_R^+ \sim \begin{pmatrix} u_R^3 \\ \nu_R^3 \end{pmatrix} \qquad \psi_R^- \sim \begin{pmatrix} d_R^3 \\ e_R^3 \end{pmatrix} \qquad \chi_{L,R} \sim \begin{pmatrix} Q_{L,R} \\ L_{L,R} \end{pmatrix}$$

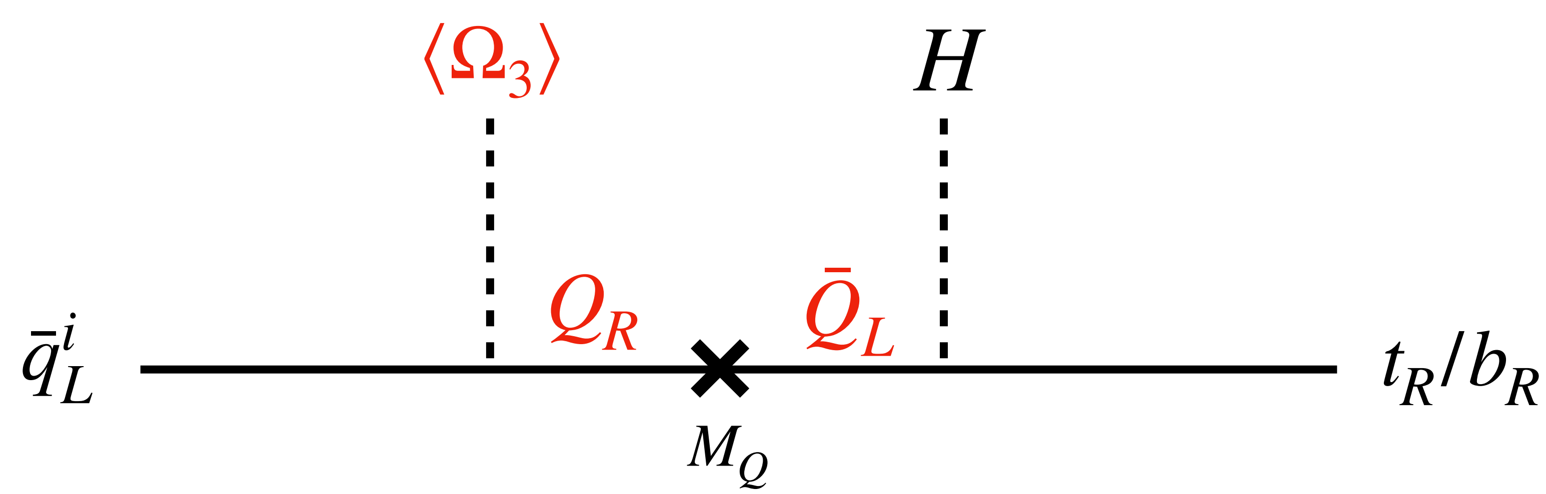
UV Model: The origin of light-heavy CKM mixing

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

$$\psi_L \sim \begin{pmatrix} q_L^3 \\ \ell_L^3 \end{pmatrix} \qquad \psi_R^+ \sim \begin{pmatrix} u_R^3 \\ \nu_R^3 \end{pmatrix} \qquad \psi_R^- \sim \begin{pmatrix} d_R^3 \\ e_R^3 \end{pmatrix} \qquad \chi_{L,R} \sim \begin{pmatrix} Q_{L,R} \\ L_{L,R} \end{pmatrix}$$

- CKM mixing via a vector-like quark. Generates V_{cb} , V_{ub} as dimension-5 operators.

$$\mathscr{L}_{\text{mix}} \supset -\lambda_q^i \bar{q}_L^i \Omega_3 \chi_R - y_\pm \bar{\chi}_L H \Psi_R^\pm \quad \longrightarrow \quad \frac{y_\pm \lambda_q^i}{M_\chi} \bar{q}_L^i \Omega_3 H \Psi_R^\pm$$



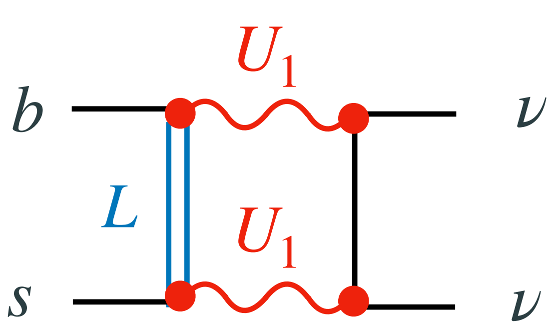
UV Model: Vector-like fermions

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

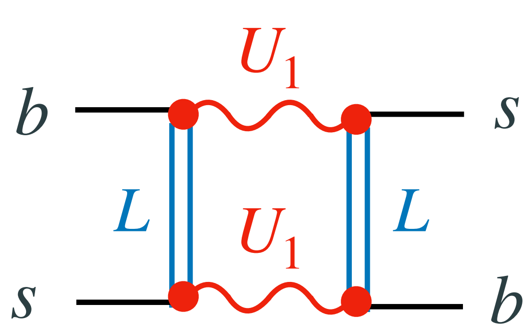
$$\psi_L \sim \begin{pmatrix} q_L^3 \\ \ell_L^3 \end{pmatrix} \qquad \psi_R^+ \sim \begin{pmatrix} u_R^3 \\ \nu_R^3 \end{pmatrix} \qquad \psi_R^- \sim \begin{pmatrix} d_R^3 \\ e_R^3 \end{pmatrix} \qquad \chi_{L,R} \sim \begin{pmatrix} Q_{L,R} \\ L_{L,R} \end{pmatrix}$$

Vector-like Lepton:

- Controls loop FCNC's



$$B \to K\nu\bar{\nu} \propto M_L$$



$$\Delta M_{B_s} \propto M_L^2$$

[CMS-PAS-B2G-21-004]: $M_L \gtrsim 500$ GeV

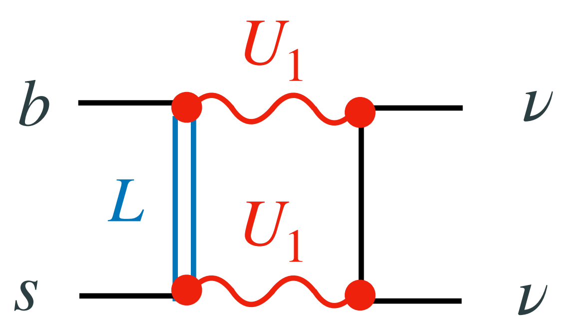
UV Model: Vector-like fermions

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

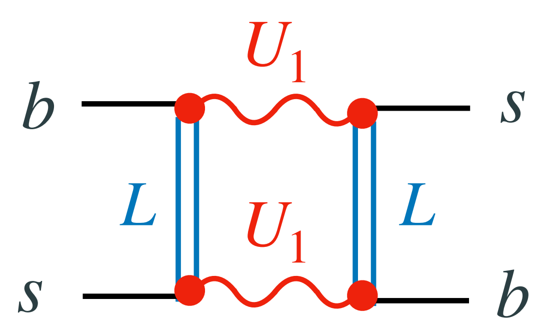
$$\psi_L \sim \begin{pmatrix} q_L^3 \\ \ell_L^3 \end{pmatrix} \qquad \psi_R^+ \sim \begin{pmatrix} u_R^3 \\ \nu_R^3 \end{pmatrix} \qquad \psi_R^- \sim \begin{pmatrix} d_R^3 \\ e_R^3 \end{pmatrix} \qquad \chi_{L,R} \sim \begin{pmatrix} Q_{L,R} \\ L_{L,R} \end{pmatrix}$$

Vector-like Lepton:

- Controls loop FCNC's



$$B \to K\nu\bar{\nu} \propto M_L$$



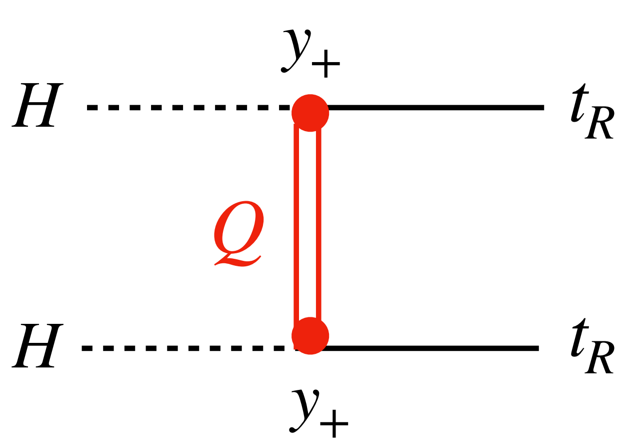
$$\Delta M_{B_s} \propto M_L^2$$

[CMS-PAS-B2G-21-004]: $M_L \gtrsim 500$ GeV

Vector-like Quark:

- CKM mixing and effects in EWPO via RGE

$$\mathscr{L}_{\rm mix} \supset -y_{\pm}\bar{\chi}_L H \Psi_R^{\pm}$$



$$\to [C_{Hu}]_{33}$$

[CMS-B2G-20-011]: $M_Q \gtrsim 1.5$ TeV

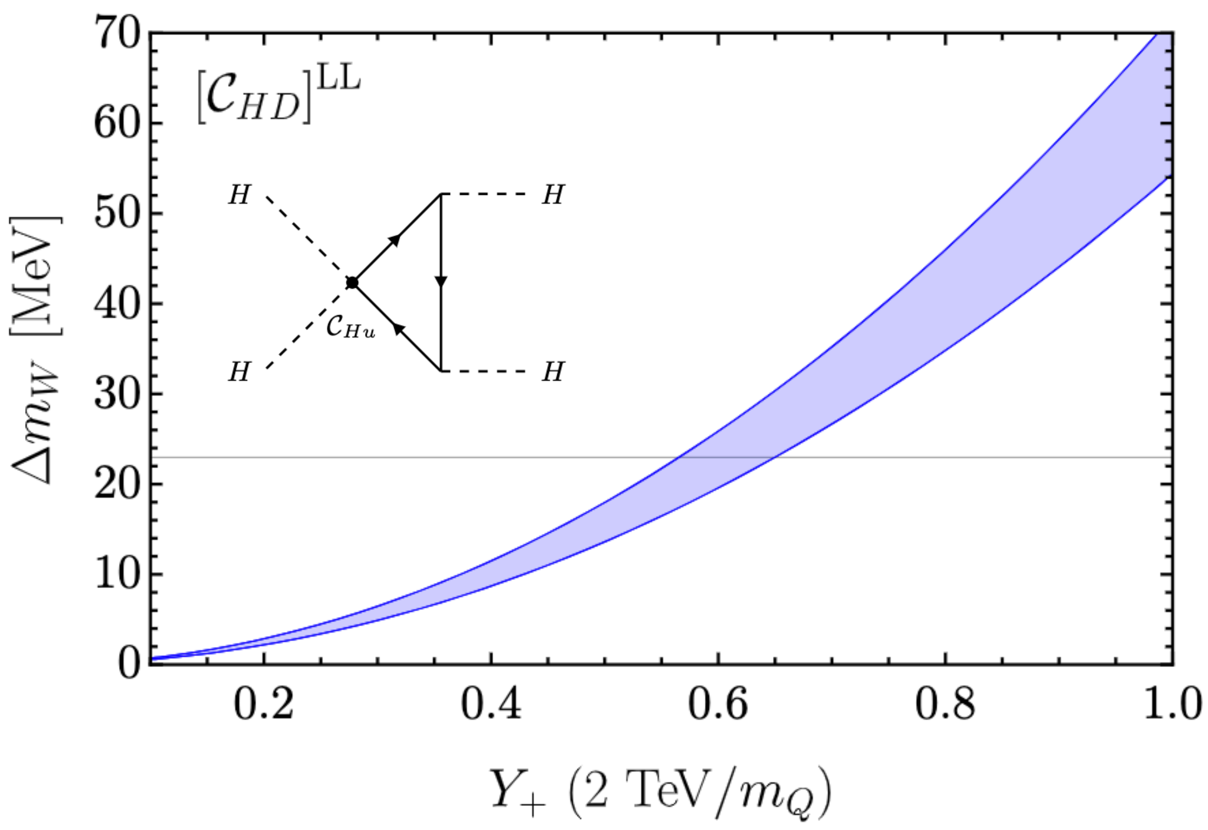
UV Model: New colored particles and EW observables

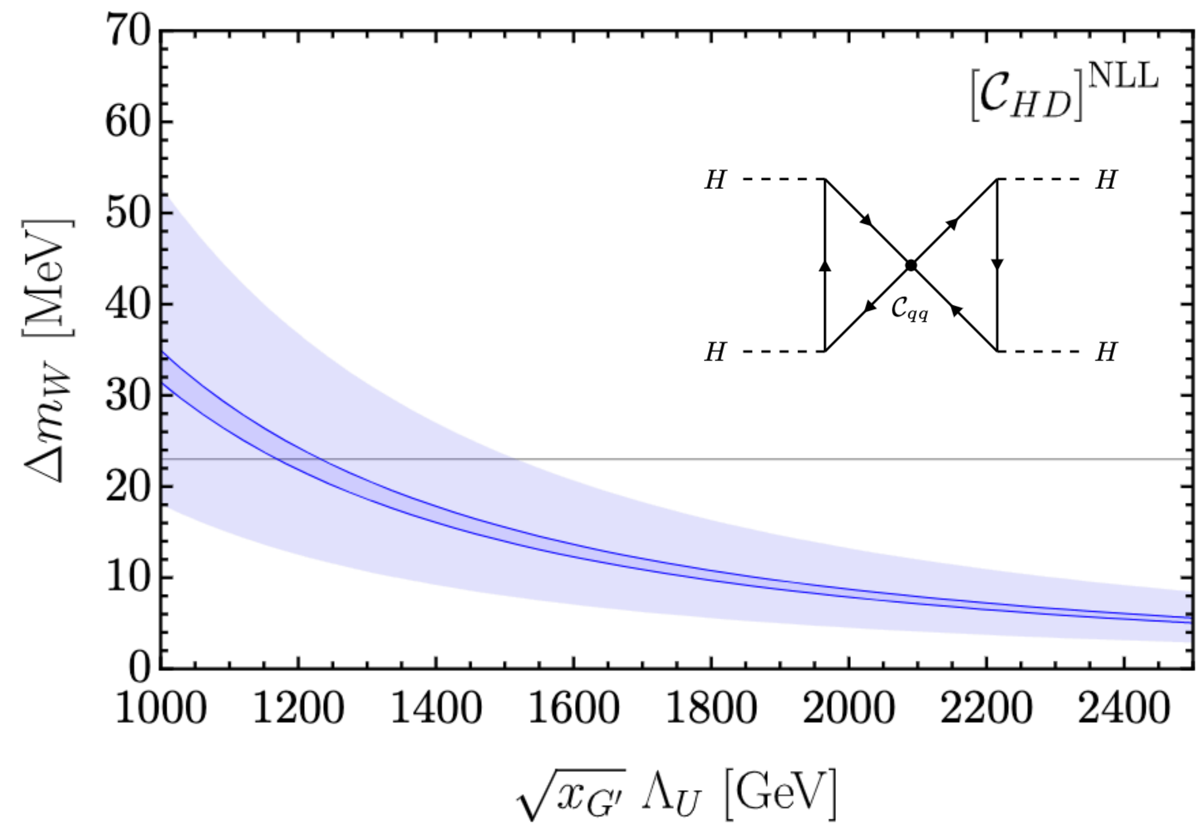
- In addition to the U_1 LQ, we also get neutral G', Z' vectors.
- We also need a vector-like quark and lepton Q, L for fermion mixing.

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.
- New colored states Q, G' give sizable shifts in the W-mass via RGE effects.

$$\frac{\Delta m_W}{m_W} \supset -\frac{v^2}{4}\frac{g_L^2}{g_L^2 - g_Y^2} C_{HD} \qquad \mathcal{O}_{HD} = |H^\dagger D_\mu H|^2 \qquad \alpha T = -\frac{v^2}{2} C_{HD}$$





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

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 $R_{K^{(*)}}$!
- Consistent picture, but present data in $b \to c\tau\nu$ require NP to be quite close: if the tension persists, NP effects must show up **soon**, at low and high energy.
- Of the mediators that can explain the charged-current B-anomalies, only the U_1 LQ connects $b \to c\tau\nu$ transitions to flavor universal effects in the $b \to s\ell\ell$ system.
- In UV complete models for the U_1 LQ (e.g. the 4321 model), CKM mixing requires the existence of light VL quarks and leptons that can be discovered at the LHC.
- The VLF's give new loop-level pheno correlated with $R_{D^{(*)}}$, such as an ~50% enhancement in $B \to K\nu\bar{\nu}$ and large positive shifts to the W-mass via RGE.
- From the phenomenological point of view, the implications of NP explanations of $R_{D^{(*)}}$ have been clear for while. To make progress, **we need more data!**

Conclusions

Thanks a lot for your attention!

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

- Consistent picture, but present data in $b \to c\tau\nu$ require NP to be quite close: if the tension persists, NP effects must show up **soon**, at low and high energy.

- Of the mediators that can explain the charged-current B-anomalies, only the U_1 LQ connects $b \to c\tau\nu$ transitions to flavor universal effects in the $b \to s\ell\ell$ system.

- In UV complete models for the U_1 LQ (e.g. the 4321 model), CKM mixing requires the existence of light VL quarks and leptons that can be discovered at the LHC.

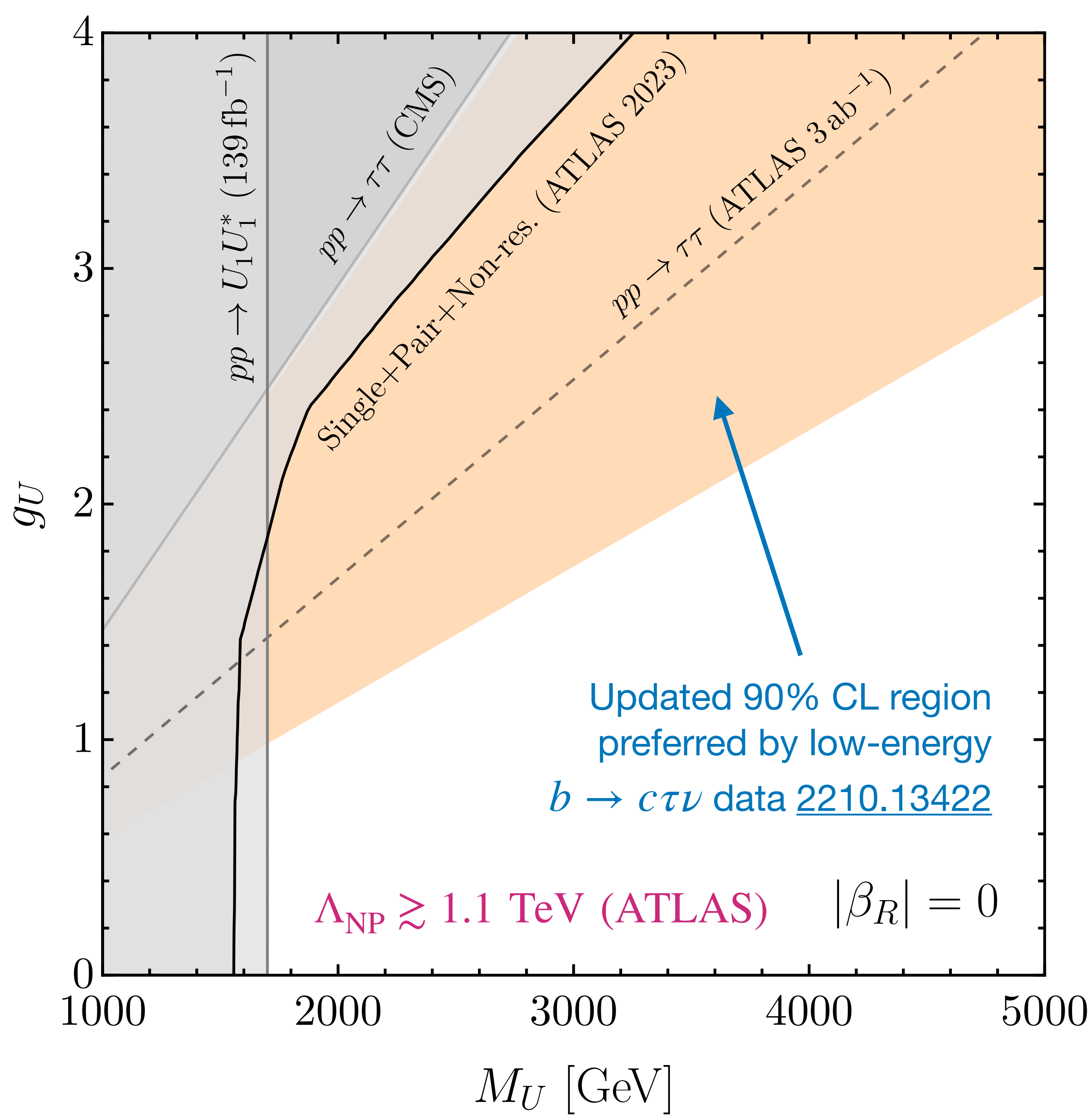
- The VLF's give new loop-level pheno correlated with $R_{D^{(*)}}$, such as an ~50% enhancement in $B \to K\nu\bar{\nu}$ and large positive shifts to the *W*-mass via RGE.

- From the phenomenological point of view, the implications of NP explanations of $R_{D^{(*)}}$ have been clear for while. To make progress, **we need more data!**

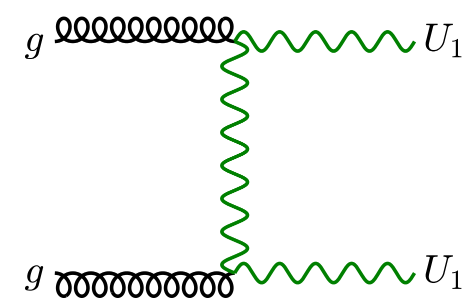
Backup Slides

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 3σ excess, ATLAS just set weaker than expected limits……too soon to say.



U_1 pair production



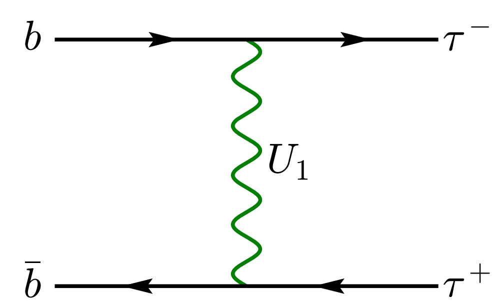
$U_1 \to b\tau^+, t\bar{\nu}$

$\mathscr{B}(U_1 \to b\tau^+) \approx 0.5$

$pp \to U_1^+ U_1^- \to b\tau\, t\nu$

2012.0417

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



2002.1222

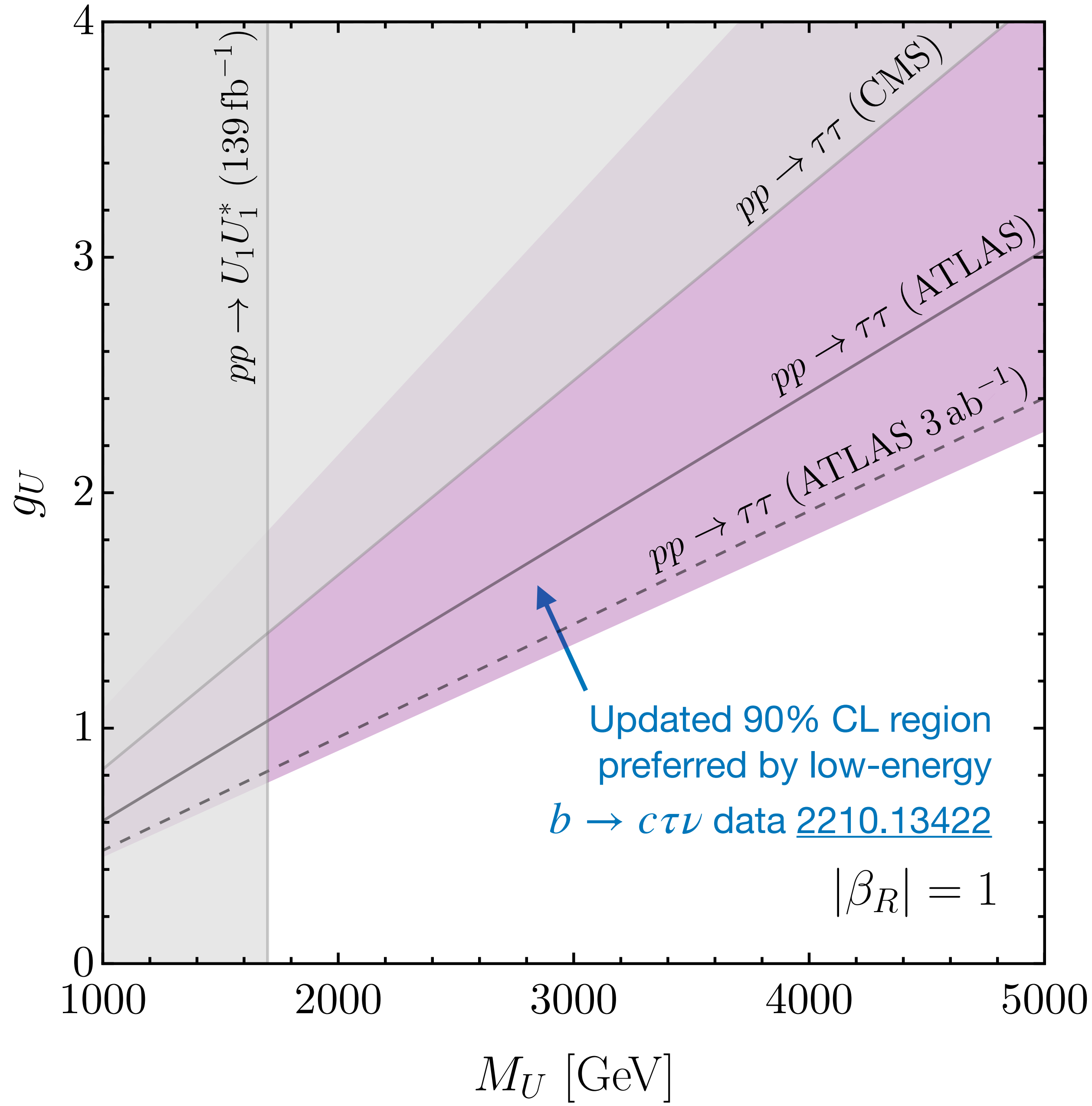
High mass Drell-Yan tails

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

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

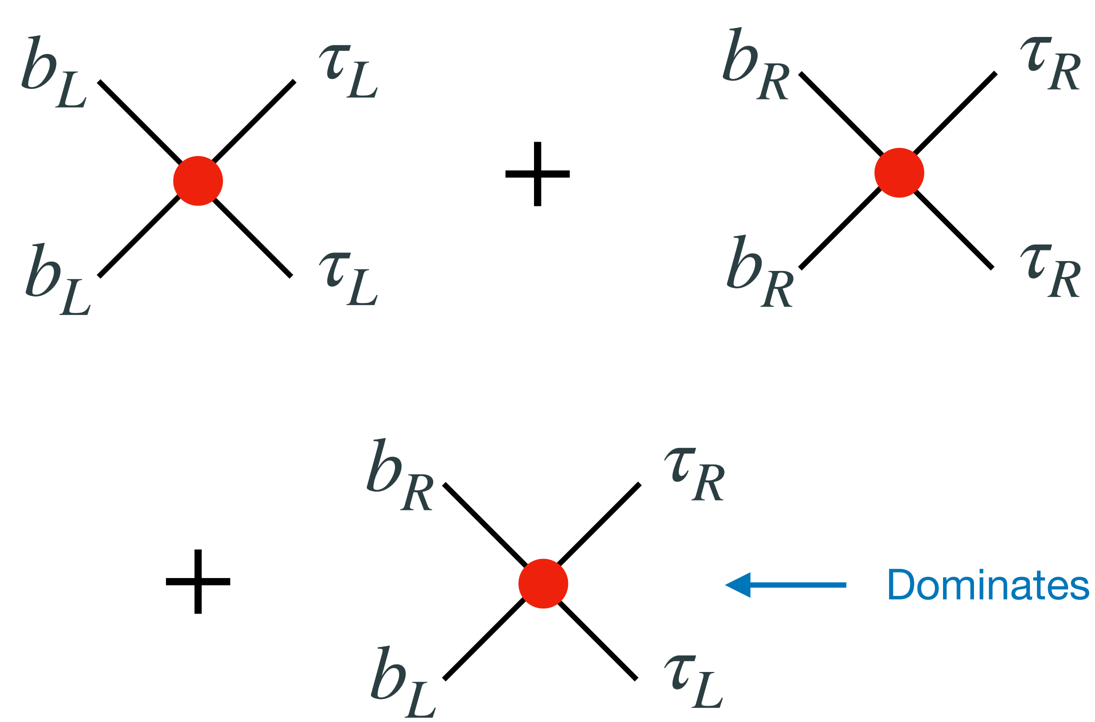
High-energy searches: U_1 leptoquark model (L&R)

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



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

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



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

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

SM

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

Vector LQ:

$U_1^\mu : C_{V_L},\, C_{S_R}$ ✓

Scalar LQs:

$R_2 : C_{S_L} = 4C_T$ ⊖

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

⊖ $R_2 : C_{S_L} = 4C_T$

$$\delta R_D = +\,7.1\,\text{Re}(C_T) + 17.2\,|C_T|^2$$
$$\delta R_{D*} = -\,5.6\,\text{Re}(C_T) + 16.7\,|C_T|^2$$

- 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.

Neutral-current B-anomalies

The $b \to s\ell\ell$ anomalies before

- Until recently, two "types" of anomalies in $b \to sll$:

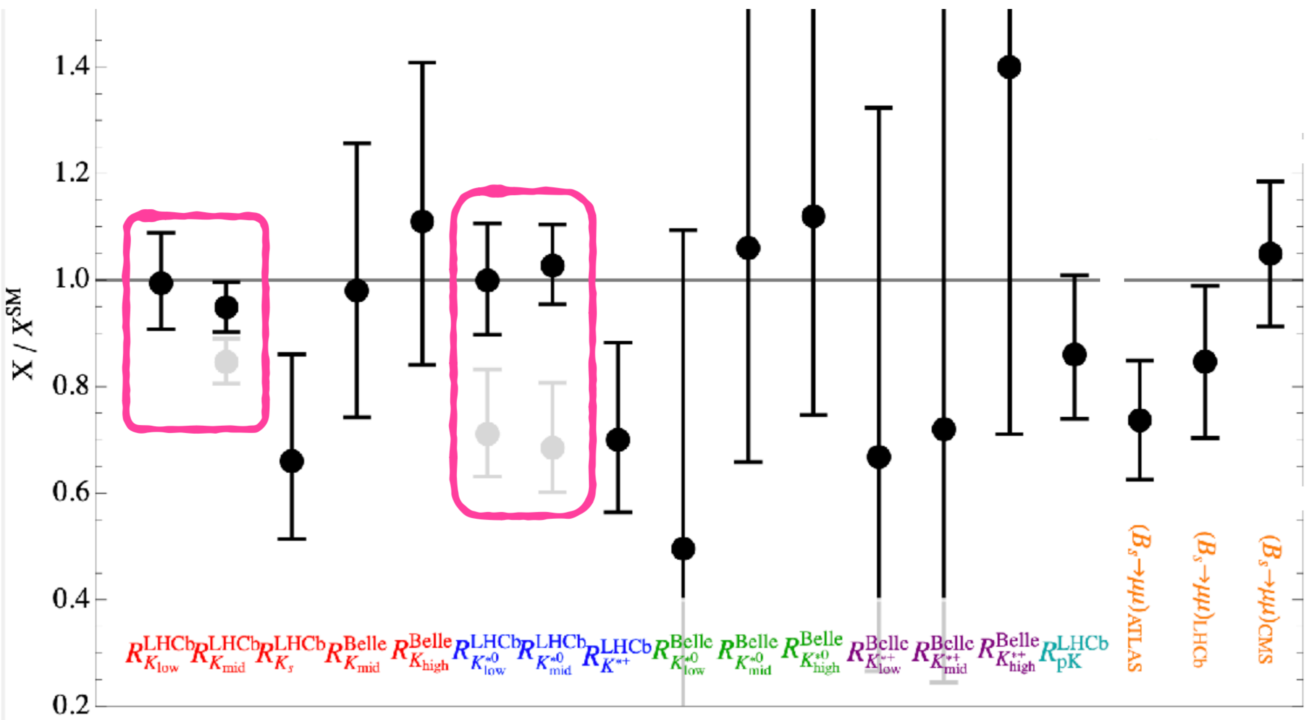
  1. μ/e universality ratios in $B \to K^{(*)}ll$
  2. discrepancies in obs. with muons only $\begin{cases} \text{ang. obs. in } B^{(0,+)} \to K^{*(0,+)}\mu^+\mu^- \\ \text{BRs of } B \to K\mu^+\mu^-, B \to K^*\mu^+\mu^-, B_s \to \phi\mu^+\mu^- \end{cases}$

The $b \to s\ell\ell$ anomalies before

- Until recently, two "types" of anomalies in $b \to sll$:

  1. μ/e universality ratios in $B \to K^{(*)}ll$
  2. discrepancies in obs. with muons only $\begin{cases} \text{ang. obs. in } B^{(0,+)} \to K^{*(0,+)}\mu^+\mu^- \\ \text{BRs of } B \to K\mu^+\mu^-, B \to K^*\mu^+\mu^-, B_s \to \phi\mu^+\mu^- \end{cases}$

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



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

$$\text{low-}q^2 \begin{cases} R_K = 0.994\,^{+0.090}_{-0.082}\,(\text{stat})^{+0.029}_{-0.027}\,(\text{syst}), \\ R_{K^*} = 0.927\,^{+0.093}_{-0.087}\,(\text{stat})^{+0.036}_{-0.035}\,(\text{syst}), \end{cases}$$

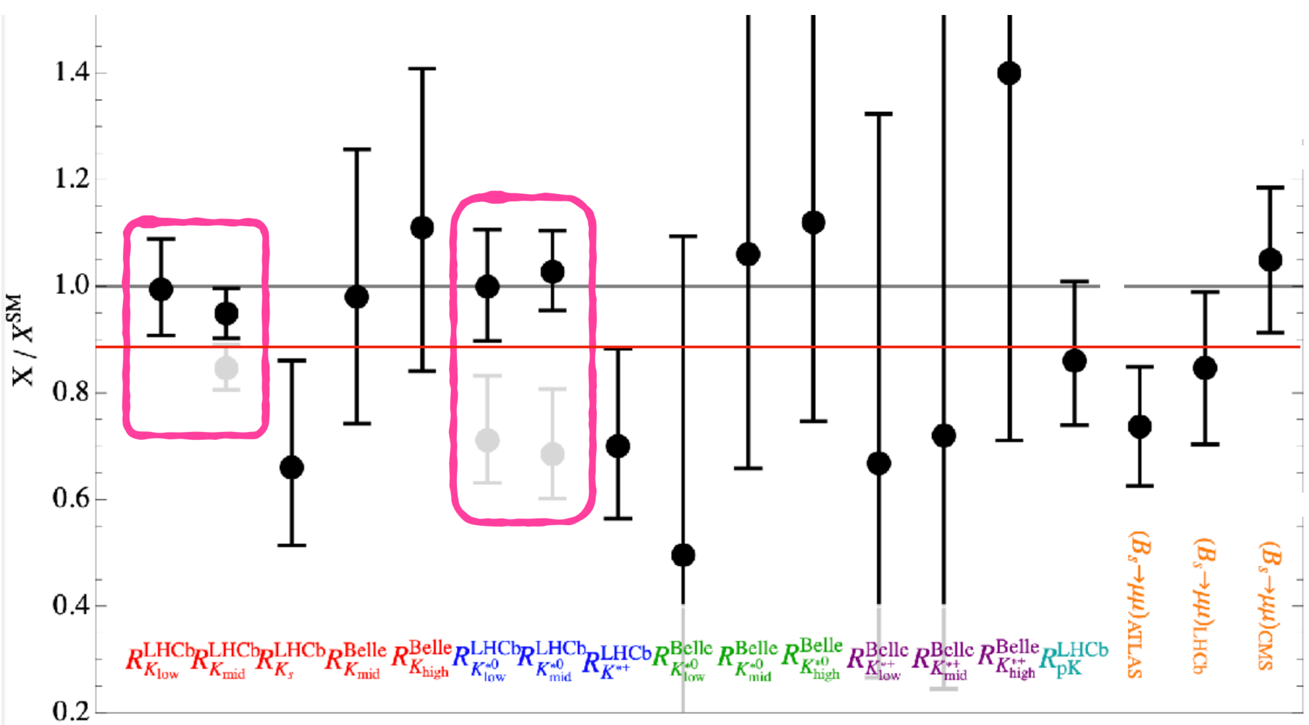
$$\text{central-}q^2 \begin{cases} R_K = 0.949\,^{+0.042}_{-0.041}\,(\text{stat})^{+0.022}_{-0.022}\,(\text{syst}), \\ R_{K^*} = 1.027\,^{+0.072}_{-0.068}\,(\text{stat})^{+0.027}_{-0.026}\,(\text{syst}). \end{cases}$$

The $b \to s\ell\ell$ anomalies before

- Until recently, two "types" of anomalies in $b \to sll$:

  1. μ/e universality ratios in $B \to K^{(*)}ll$
  2. discrepancies in obs. with muons only $\begin{cases} \text{ang. obs. in } B^{(0,+)} \to K^{*(0,+)}\mu^+\mu^- \\ \text{BRs of } B \to K\mu^+\mu^-, B \to K^*\mu^+\mu^-, B_s \to \phi\mu^+\mu^- \end{cases}$

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



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

$$\text{low-}q^2 \begin{cases} R_K &= 0.994\ ^{+0.090}_{-0.082}\,(\text{stat})^{+0.029}_{-0.027}\,(\text{syst}), \\ R_{K^*} &= 0.927\ ^{+0.093}_{-0.087}\,(\text{stat})^{+0.036}_{-0.035}\,(\text{syst}), \end{cases}$$

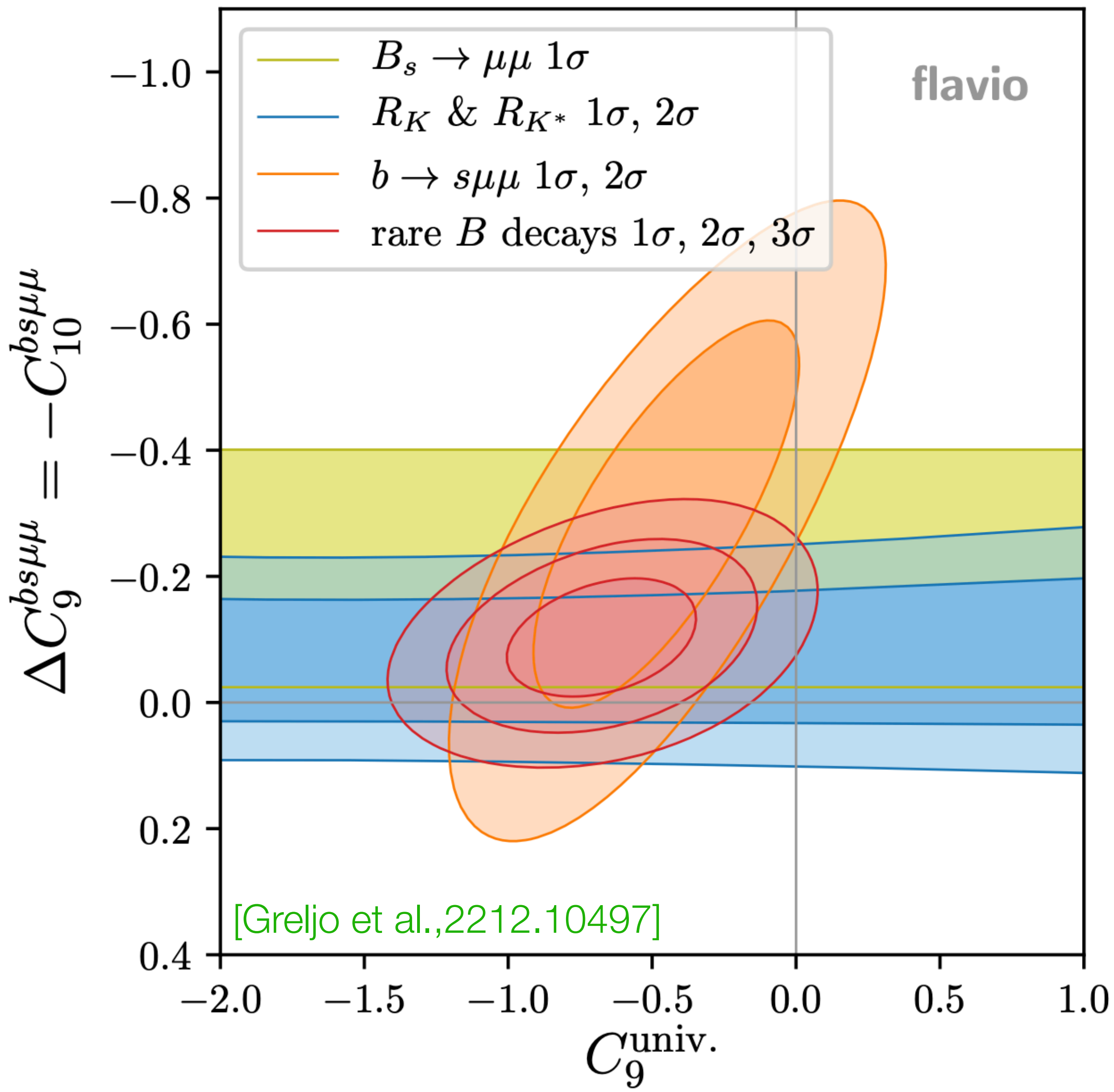
$$\text{central-}q^2 \begin{cases} R_K &= 0.949\ ^{+0.042}_{-0.041}\,(\text{stat})^{+0.022}_{-0.022}\,(\text{syst}), \\ R_{K^*} &= 1.027\ ^{+0.072}_{-0.068}\,(\text{stat})^{+0.027}_{-0.026}\,(\text{syst}). \end{cases}$$

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

The $b \to s\ell\ell$ anomalies after

$$\mathscr{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i O_i \qquad O_9^{bs\mu\mu} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \mu) \qquad O_{10}^{bs\mu\mu} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$

- Assuming NP in muons only, there's now *tension* between LFU ratios $R_{K^{(*)}}$ and BR's + P_5'

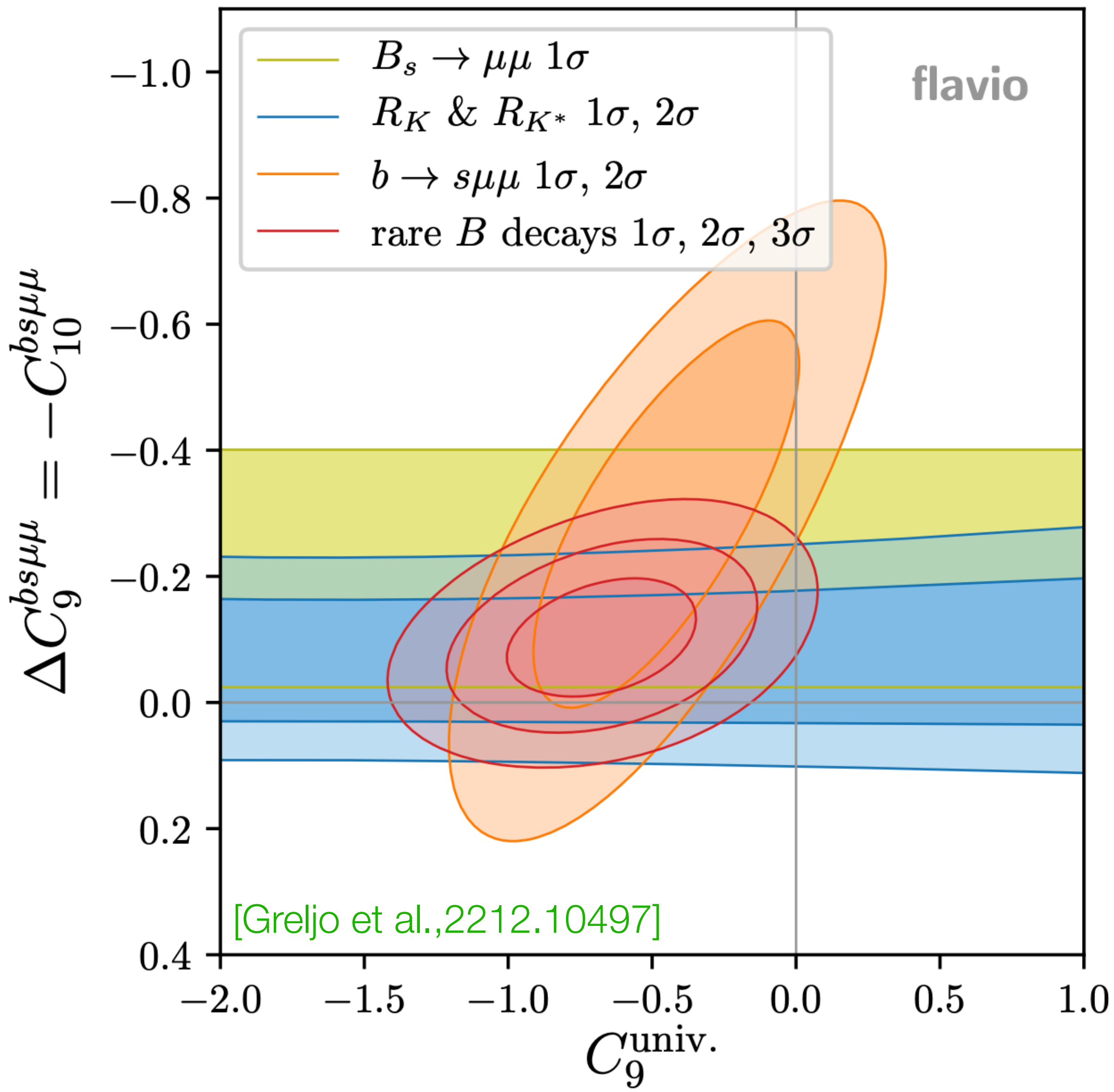


The $b \to s\ell\ell$ anomalies after

$$\mathscr{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i O_i \qquad O_9^{bs\mu\mu} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \mu) \qquad O_{10}^{bs\mu\mu} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$

- Assuming NP in muons only, there's now *tension* between LFU ratios $R_{K^{(*)}}$ and BR's + P_5'

- A flavor universal shift in C_9 is now sufficient to account for all $b \to s\mu\mu$ measurements: *LFUV component in muons only is now compatible with zero.*



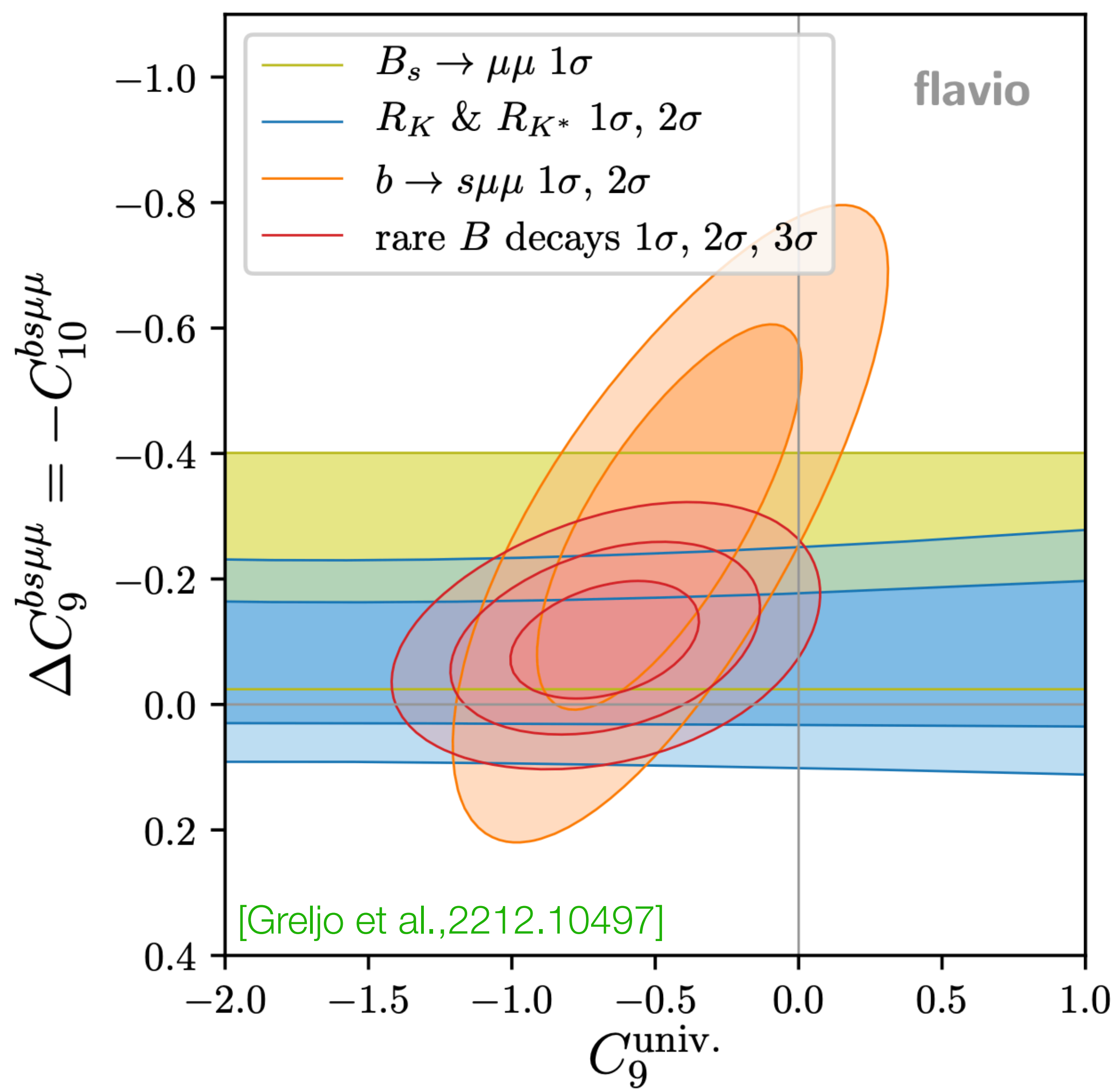
The $b \to s\ell\ell$ anomalies after

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i O_i \qquad O_9^{bs\mu\mu} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \mu) \qquad O_{10}^{bs\mu\mu} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$

- Assuming NP in muons only, there's now *tension* between LFU ratios $R_{K^{(*)}}$ and BR's + P_5'

- A flavor universal shift in C_9 is now sufficient to account for all $b \to s\mu\mu$ measurements: *LFUV component in muons only is now compatible with zero.*

✳ But, non-trivial to distinguish from long-distance QCD ("charming penguins")



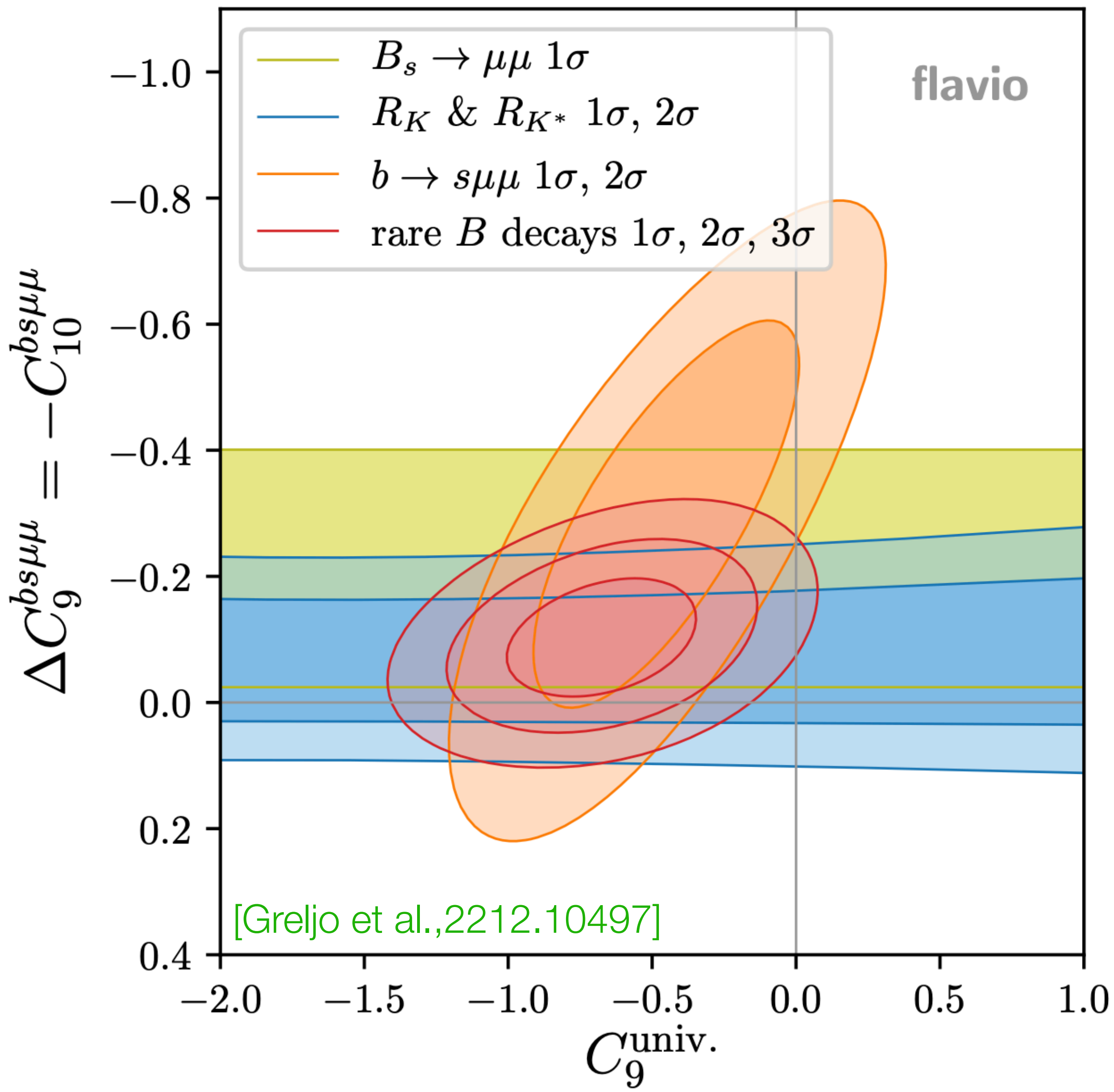
To understand these contributions better:

- 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]

What changed? Implications for model building

$$\mathscr{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i O_i \qquad O_9^{bs\mu\mu} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \mu) \qquad O_{10}^{bs\mu\mu} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$

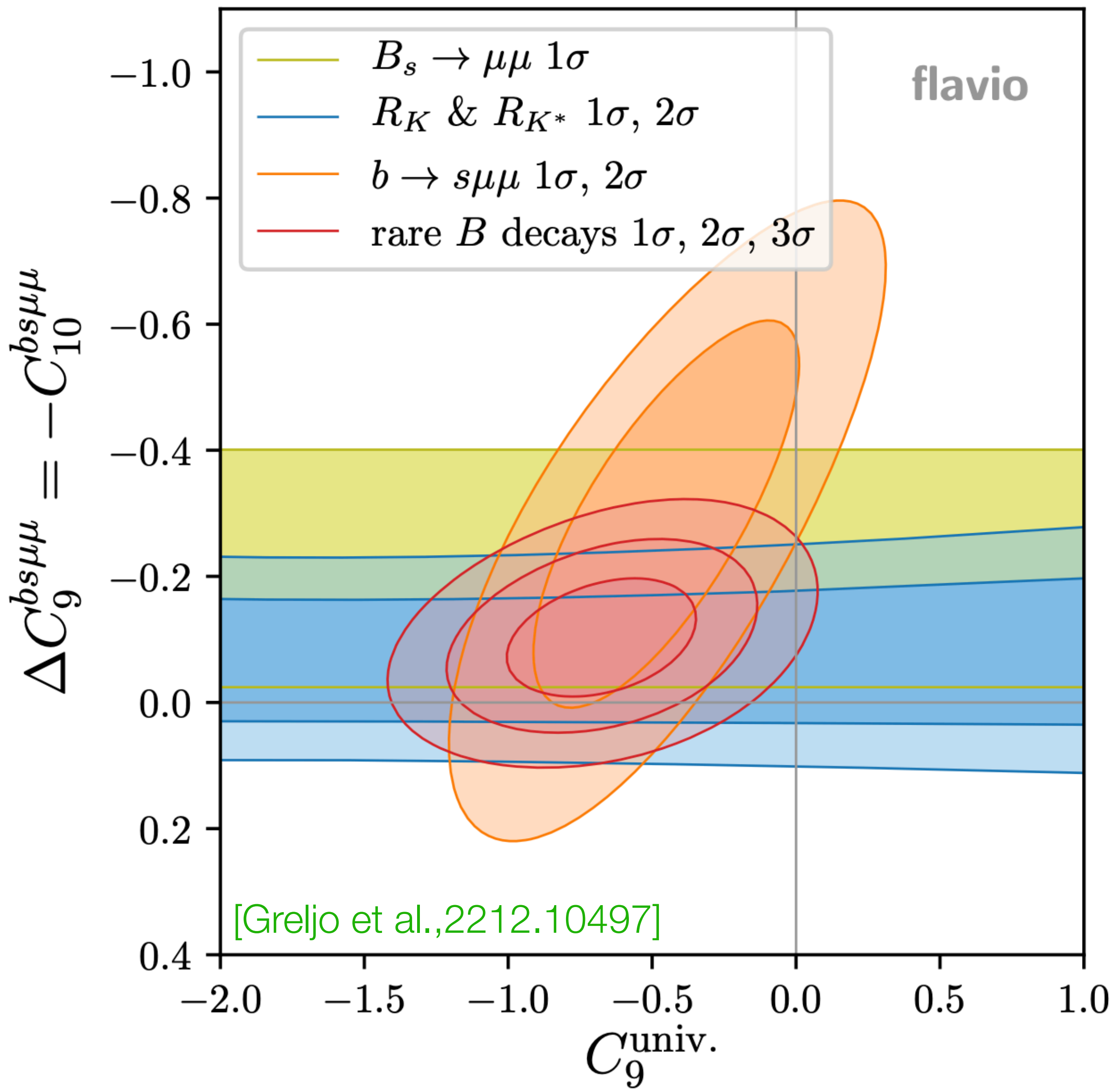
- A flavor universal shift in C_9 is now sufficient to account for all $b \to s\mu\mu$ measurements.



What changed? Implications for model building

$$\mathscr{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i O_i \qquad O_9^{bs\mu\mu} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu} \gamma^\mu \mu) \qquad O_{10}^{bs\mu\mu} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu} \gamma^\mu \gamma_5 \mu)$$

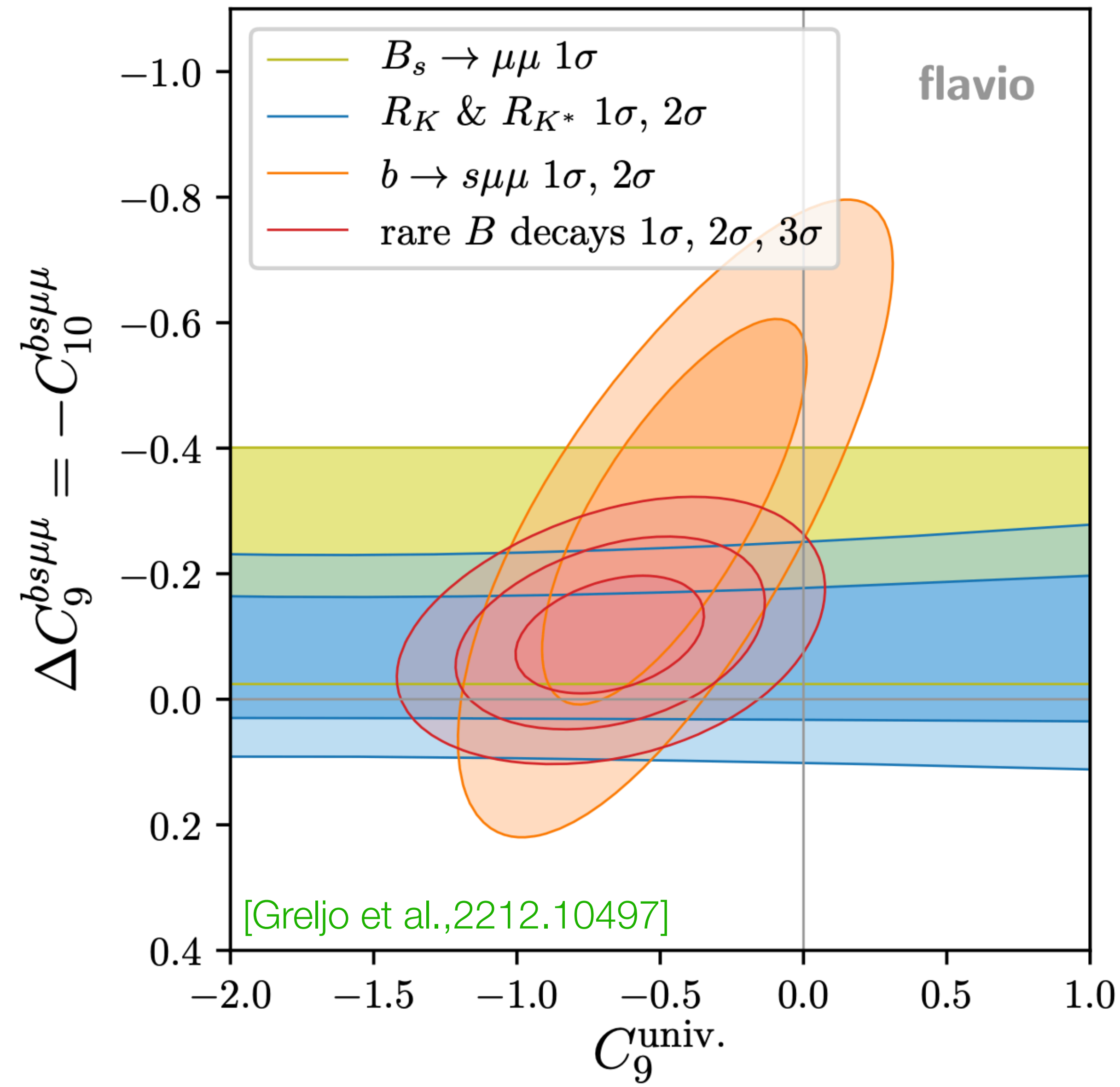
- A flavor universal shift in C_9 is now sufficient to account for all $b \to s\mu\mu$ measurements.
- Old models for combined explanation of $R_{D^{(*)}}$ and $R_{K^{(*)}}$ now must be μ/e universal at the $\sim 10\,\%$ level. This is not difficult to achieve. The main consequence: LFV effects now predicted to be small (e.g. $B \to K\tau\mu$, $B_s \to \tau\mu$, $\tau \to \mu X$ w/ $X = \ell\bar{\ell}, \phi, \gamma$)



What changed? Implications for model building

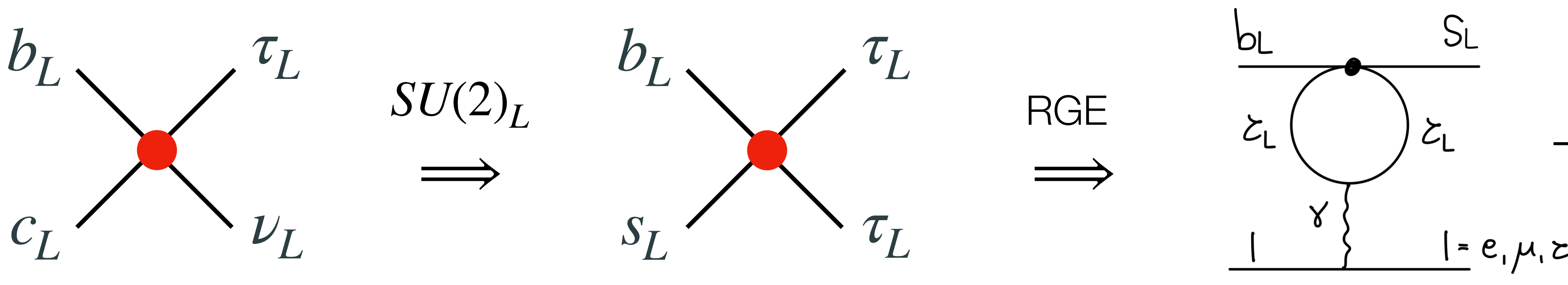
$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i O_i \qquad O_9^{bs\mu\mu} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \mu) \qquad O_{10}^{bs\mu\mu} = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$

- A flavor universal shift in C_9 is now sufficient to account for all $b \to s\mu\mu$ measurements.
- Old models for combined explanation of $R_{D^{(*)}}$ and $R_{K^{(*)}}$ now must be μ/e universal at the $\sim 10\,\%$ level. This is not difficult to achieve. The main consequence: LFV effects now predicted to be small (e.g. $B \to K\tau\mu$, $B_s \to \tau\mu$, $\tau \to \mu X$ w/ $X = \ell\bar{\ell}, \phi, \gamma$)
- Still interesting to consider models for $R_{D^{(*)}}$ (unaffected) that also give flavor universal contributions to the $b \to s\ell\ell$ system.



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

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



$\to \Delta C_9^U = C_9^U - C_9^{\rm SM}$

$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i^\ell O_i^\ell \qquad O_9^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$

- Leading-log running in SM gauge couplings gives

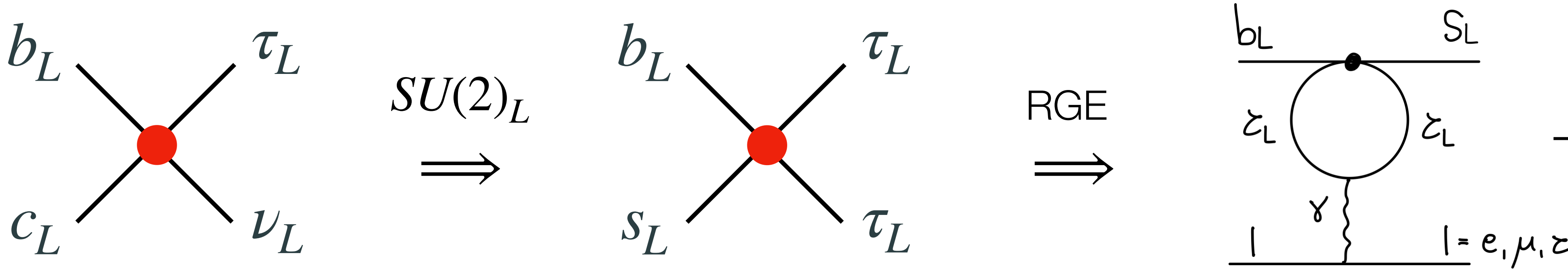
$$\Delta C_9^U = \frac{v_{\rm EW}^2}{3V_{tb}V_{ts}^*}\left([C_{lq}^{(3)}]_{\alpha\alpha 23} + [C_{lq}^{(1)}]_{\alpha\alpha 23} + [C_{qe}]_{23\alpha\alpha}\right)\log\left(\frac{m_b^2}{M^2}\right)$$

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

[Bobeth, Haisch, 1109.1826; Crivellin et al., 1807.02068; Algueró et al., 1809.08447]

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

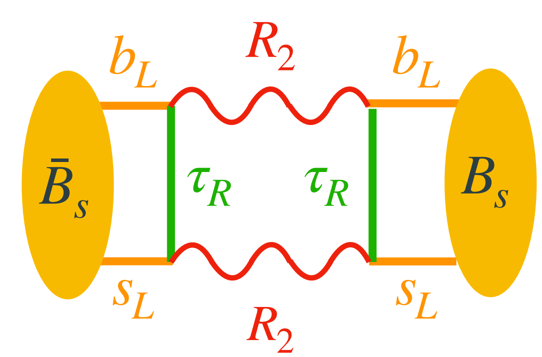
- Some vector semi-leptonics that explain the charged-current anomalies give a *flavor universal* effect in $b \to s\ell\ell$ via RGE:



$\to \Delta C_9^U = C_9^U - C_9^{\rm SM}$

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

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

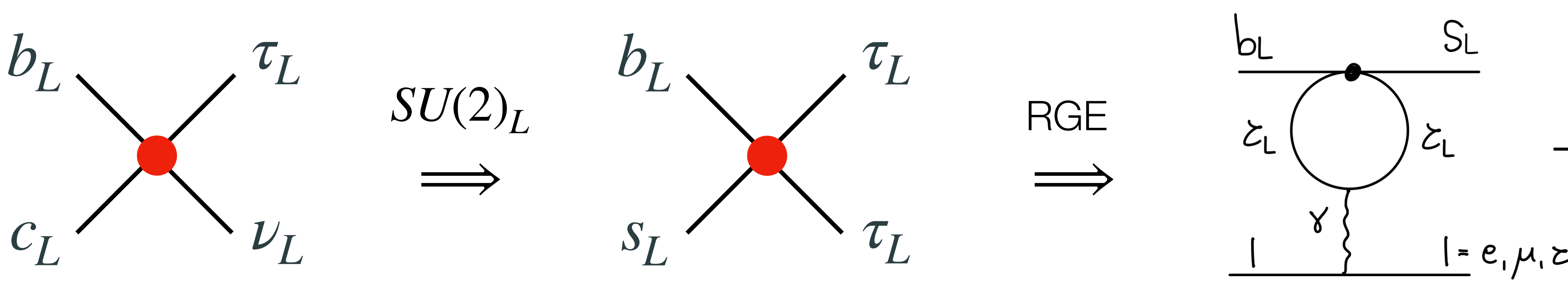


*With both $[C_{qe}]_{3333}$ & $[C_{qe}]_{2333}$ active

[Bobeth, Haisch, 1109.1826; Crivellin et al., 1807.02068; Algueró et al., 1809.08447]

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

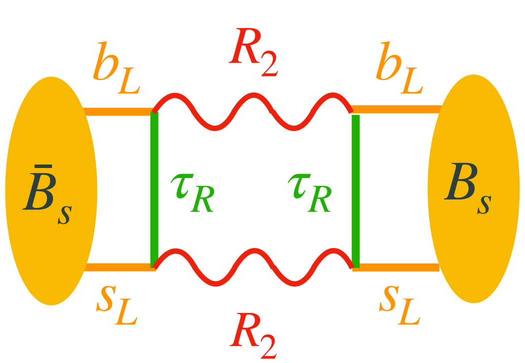
- Some vector semi-leptonics that explain the charged-current anomalies give a *flavor universal* effect in $b \to s\ell\ell$ via RGE:



$\to \Delta C_9^U = C_9^U - C_9^{\rm SM}$

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

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

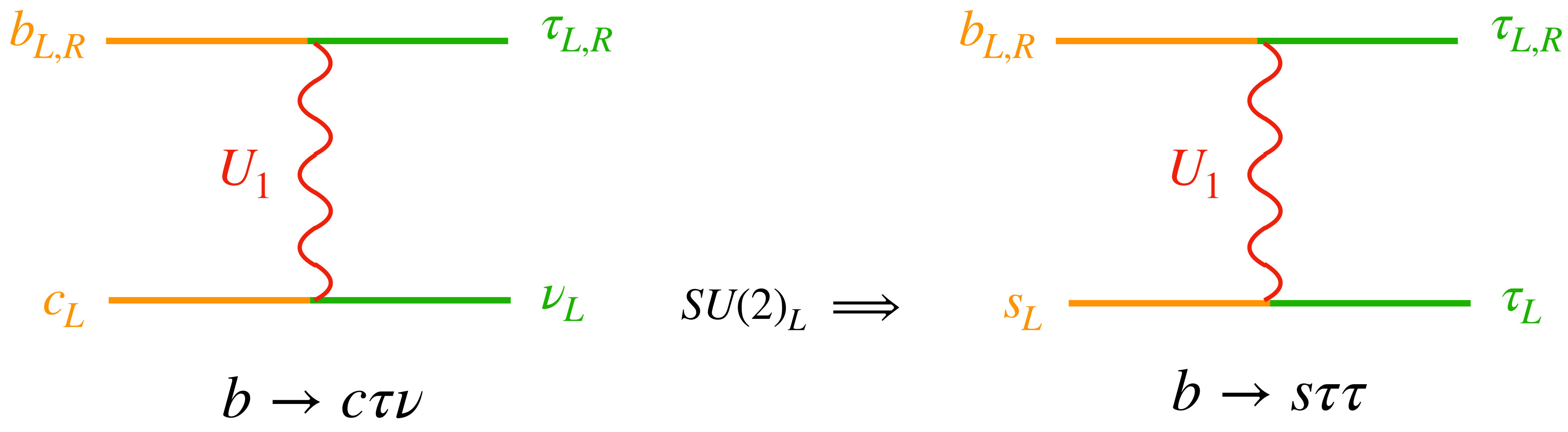


*With both $[C_{qe}]_{3333}$ & $[C_{qe}]_{2333}$ active

[Bobeth, Haisch, 1109.1826; Crivellin et al., 1807.02068; Algueró et al., 1809.08447]

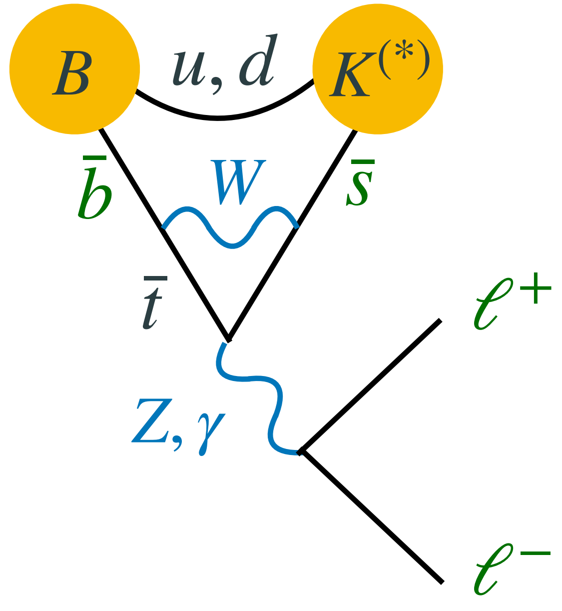
U_1 connects $R_{D^{(*)}}$ to $b \to s\tau\tau$ observables

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



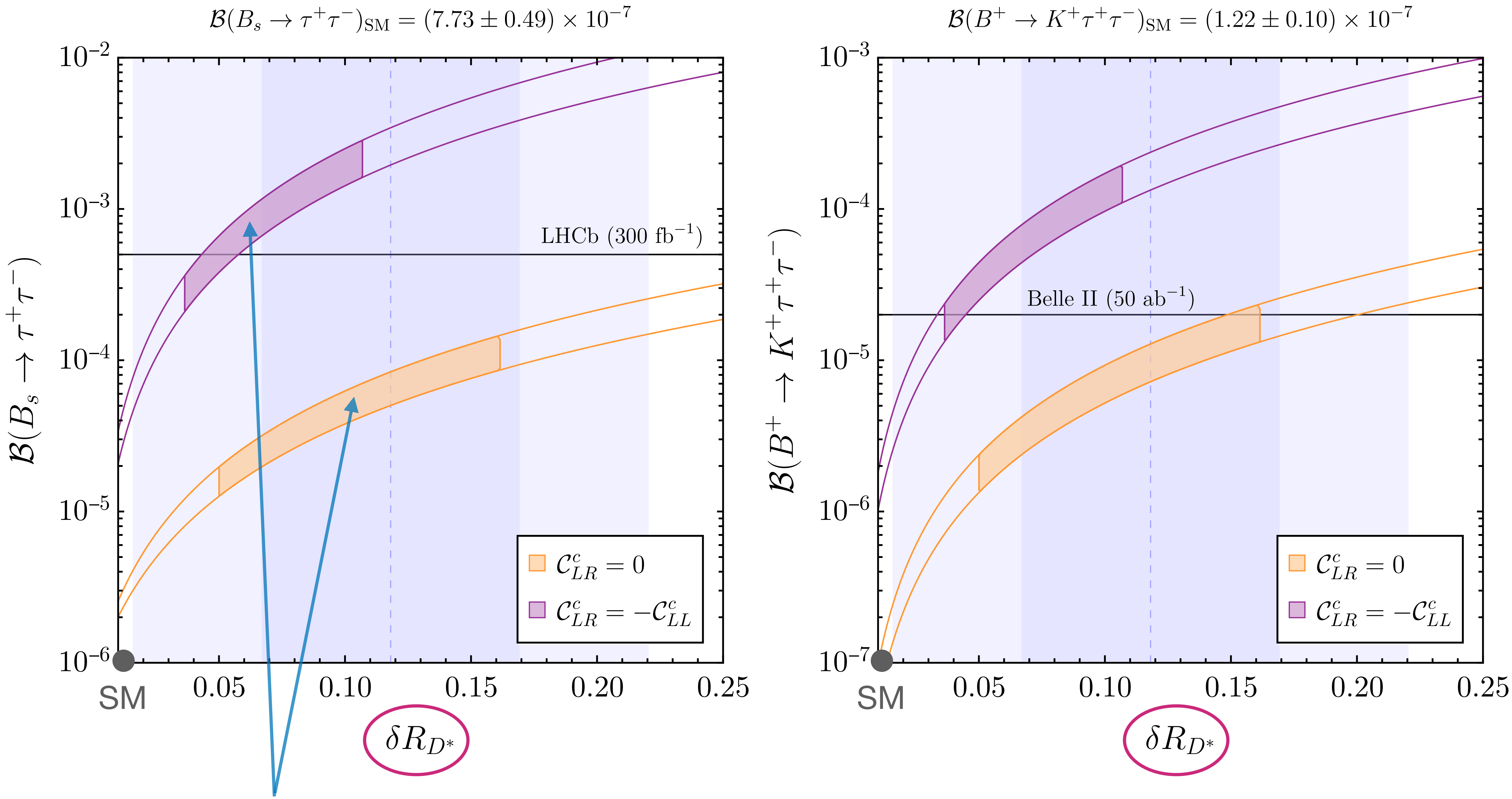
- Since $b \to s\tau\tau$ is a FCNC, it is a 1-loop process in the SM. We therefore expect a huge NP enhancement in $b \to s\tau\tau$!

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



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

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

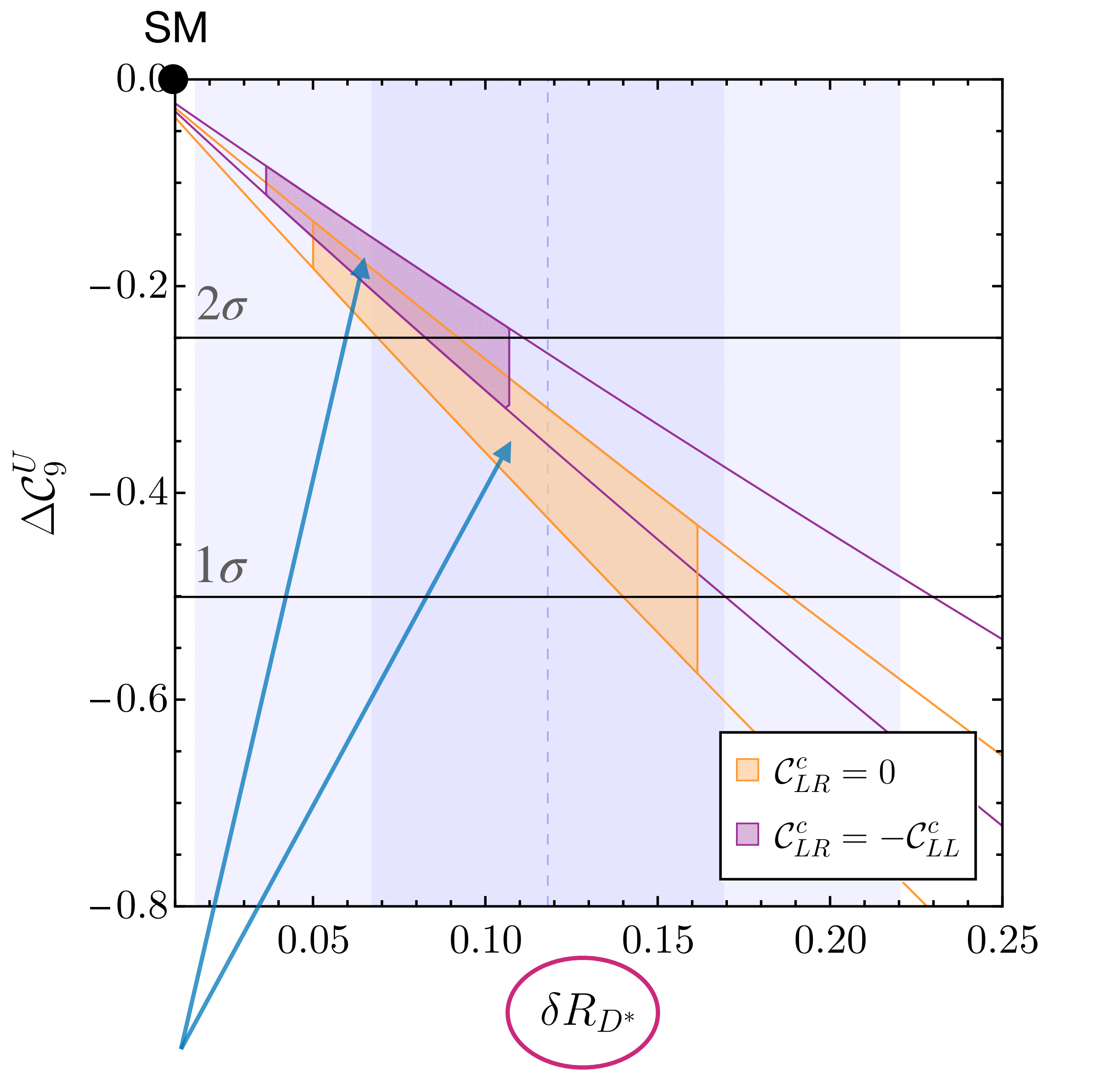


Updated 90% CL region preferred by low-energy $b \to c\tau\nu$ data 2210.13422

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

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

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

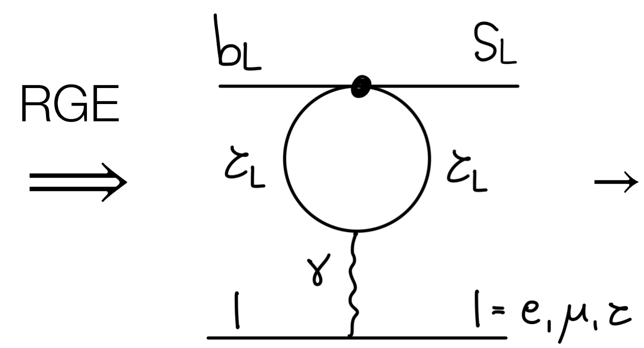


Updated 90% CL region preferred by low-energy $b \to c\tau\nu$ data 2210.13422

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

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

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



$\to \Delta C_9^U = C_9^U - C_9^{\rm SM}$

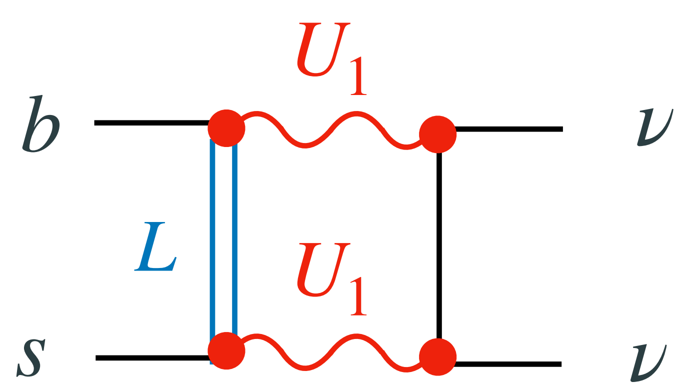
"Dirty" $b \to s\ell^+\ell^-$ data prefers:

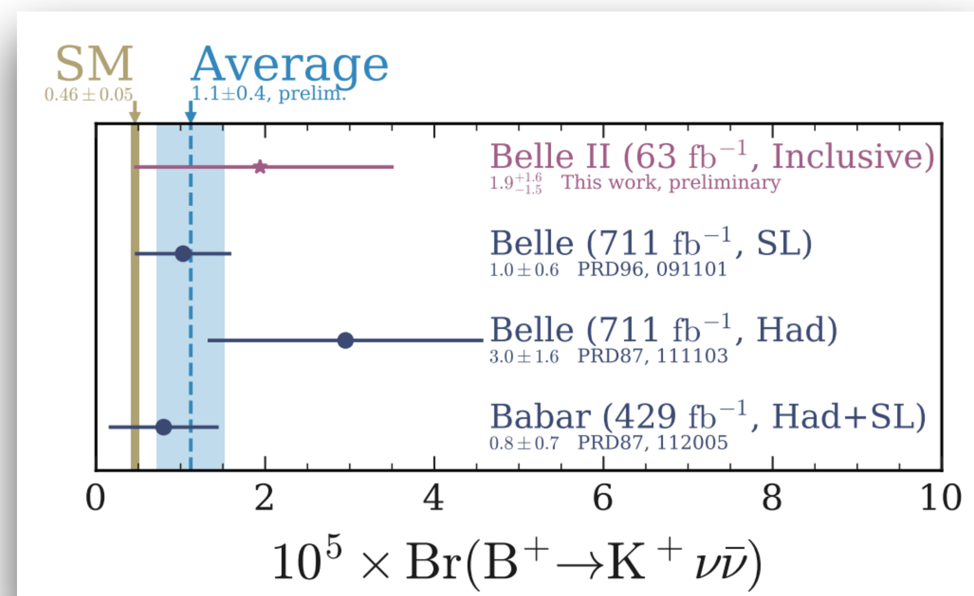
$$\Delta C_9^U \approx 0.75 \pm 0.25$$

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

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

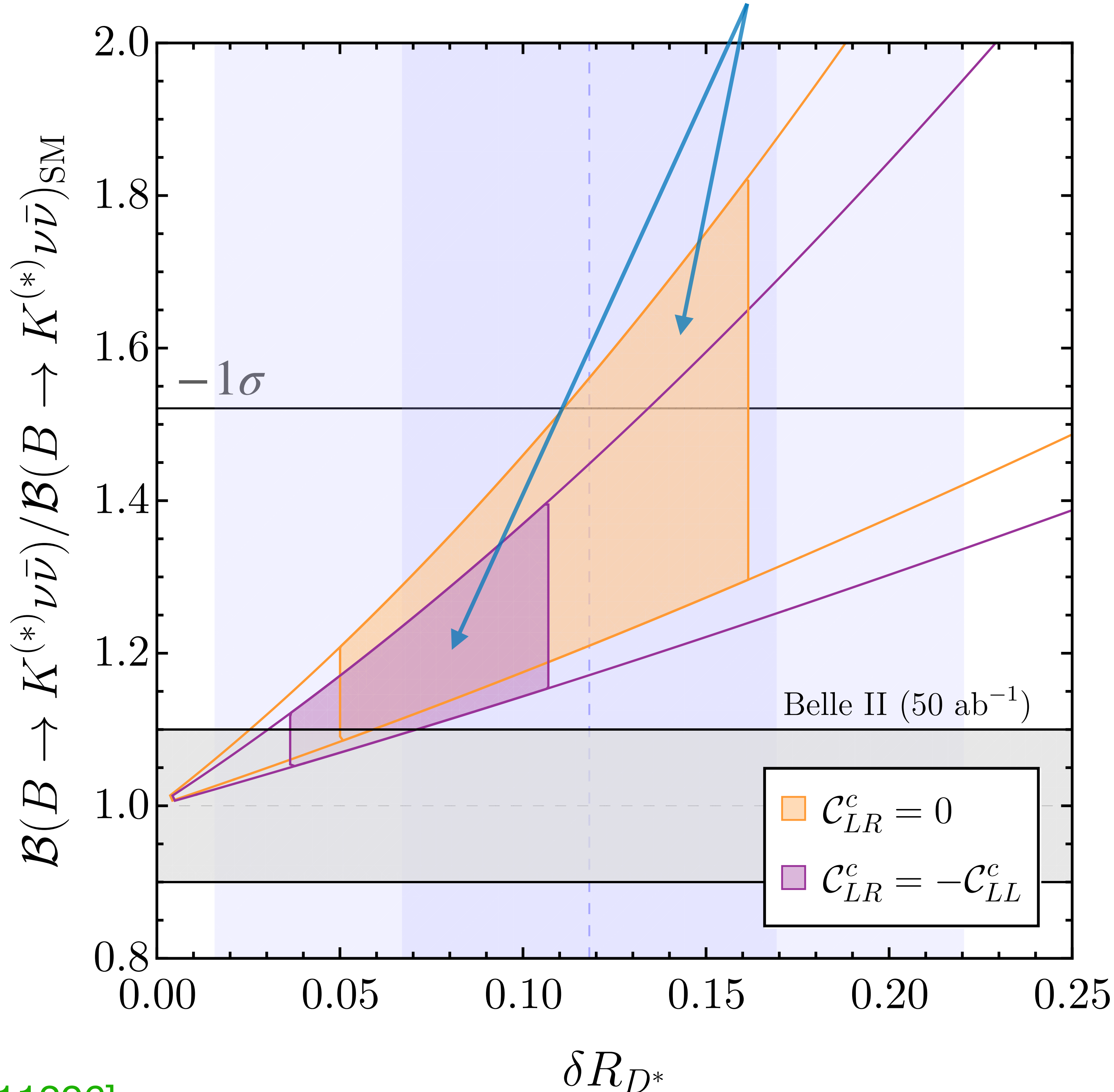
- Some (important) effects appear only at one loop. For U_1, requires UV model!





[Belle II Collaboration, 2104.12624]

Updated 90% CL region preferred by low-energy $b \to c\tau\nu$ data 2210.13422



[Fuentes-Martin, Isidori, König, Selimovic, 2009.11296]

Wrapping Up

Overview of ongoing LFU measurements

mode	Run 1: 3 fb^{-1} at 7/8 TeV muonic	Run 1: 3 fb^{-1} at 7/8 TeV hadronic	Run 2: 6 fb^{-1} at 13 TeV muonic	Run 2: 6 fb^{-1} at 13 TeV 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 $b \to u$ sector; and excited states: $\mathscr{R}(D^{**})$, $\mathscr{R}(D_s^{**})$

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 $b \to c\tau\nu$ process is the same, NP expected in all of these!

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

SM

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

SMEFT-LEFT Matching:

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

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

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

$$C_{S_R} = -\frac{v^2}{2}\sum_{i=1}^{3}\frac{V_{2i}^*}{V_{23}}\big[\mathcal{C}_{ledq}\big]^*_{333i}\,,$$

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

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

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]

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

SM

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

SMEFT-LEFT Matching:

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

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

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

$$C_{S_R} = -\frac{v^2}{2}\sum_{i=1}^{3}\frac{V_{2i}^*}{V_{23}}\,[\mathcal{C}_{ledq}]^*_{333i}\,,$$

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

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

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]

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

SM

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

SMEFT-LEFT Matching:

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

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

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

$$C_{S_R} = -\frac{v^2}{2}\sum_{i=1}^{3}\frac{V_{2i}^*}{V_{23}}\big[\mathcal{C}_{ledq}\big]^*_{333i}\,,$$

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

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

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]

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

SM

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

SMEFT-LEFT Matching:

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

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

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

$$C_{S_R} = -\frac{v^2}{2}\sum_{i=1}^{3}\frac{V_{2i}^*}{V_{23}}\big[\mathcal{C}_{ledq}\big]^*_{333i}\,,$$

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

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

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]

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

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

$$R_D\,,\; R_{D^*}\,,\; R_{\Lambda_c}$$

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

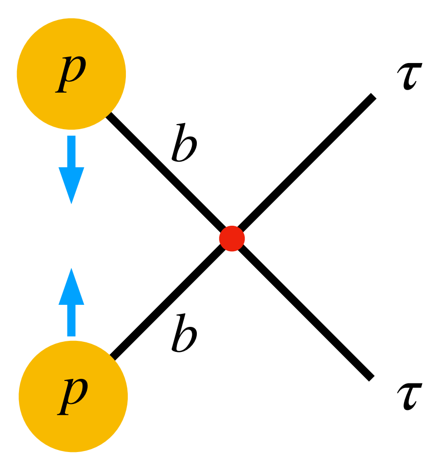
- τ-decays and EW precision observables (EWPO) [LL running in y_t, g_L, g_Y]

$Z + W$ pole observables $+$ LFU tests in τ-decays: g_W^τ / g_W^ℓ

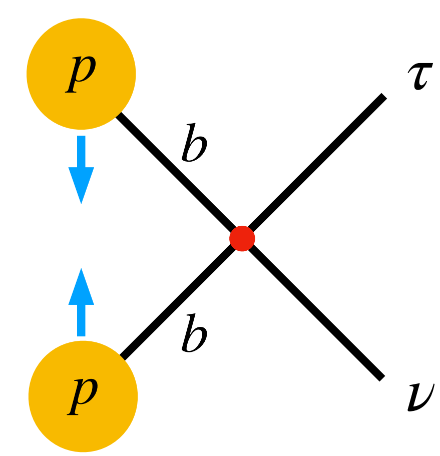
[L. Allwicher, G. Isidori, J. M. Lizana, N. Selimovic, BAS, 2302.11584]

- 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]

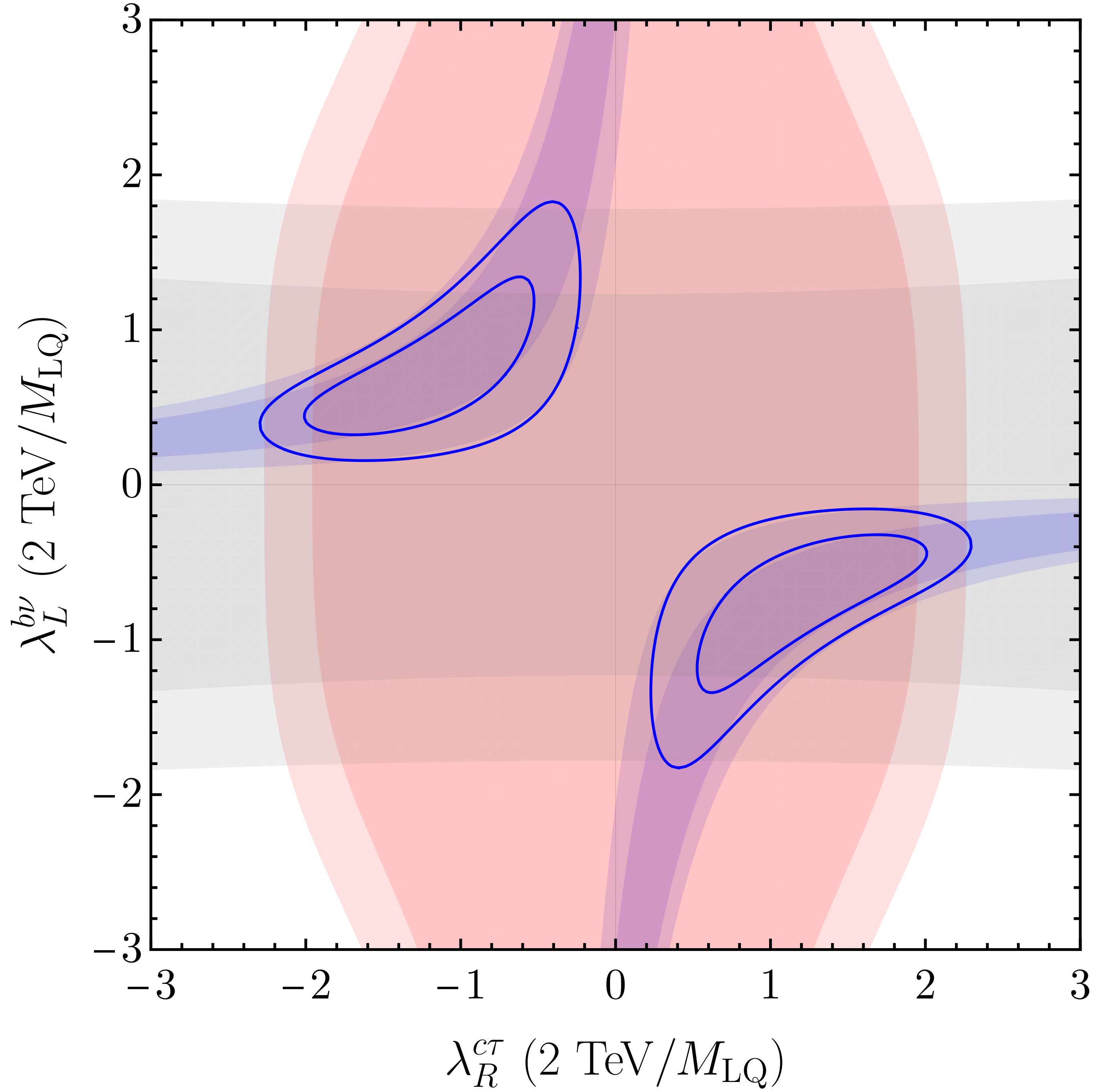


$+$



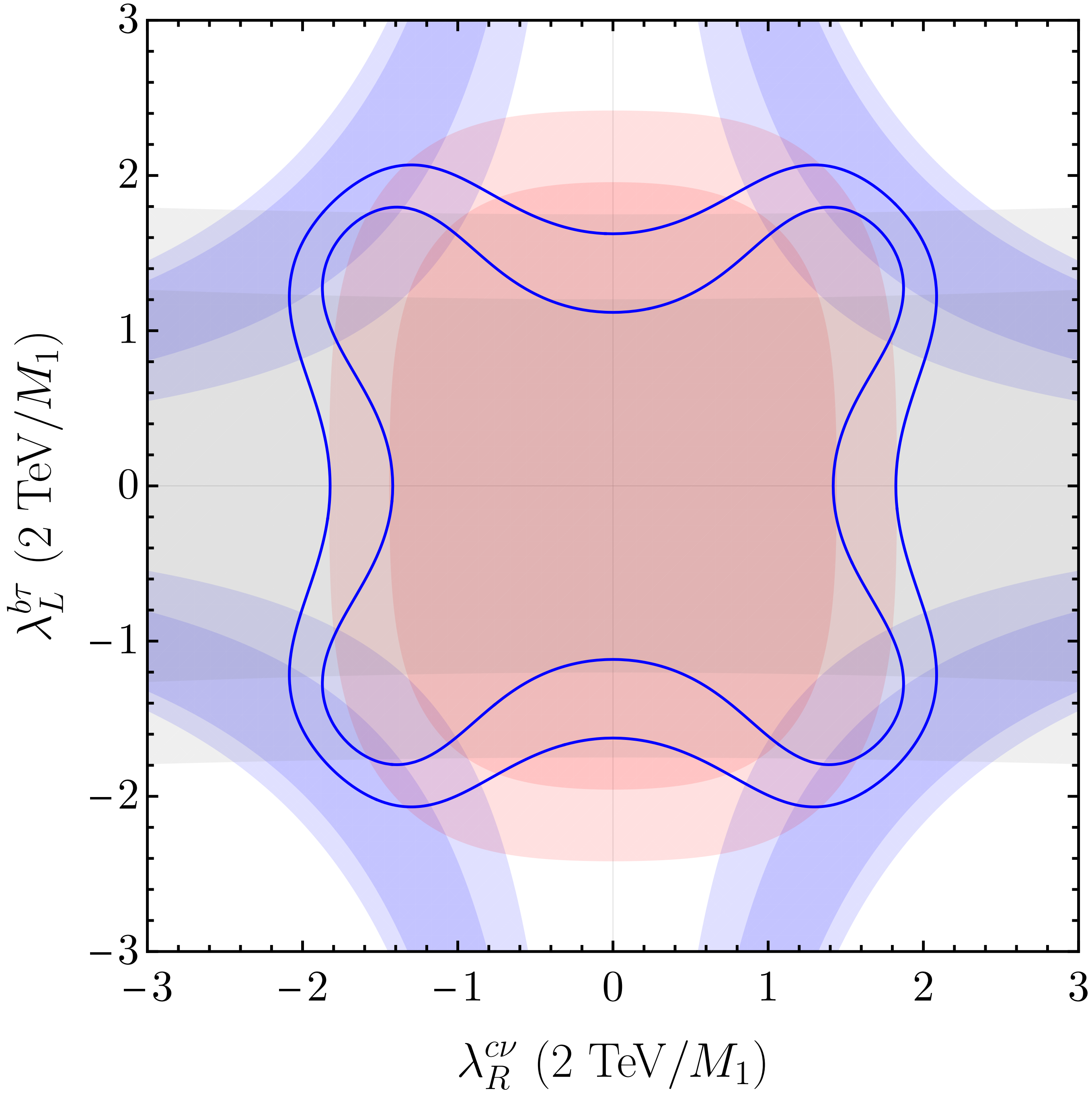
Simplified S_1 scalar LQ model and fit

$$\mathscr{L} \supset \lambda_L^{b\nu}\, \bar{q}_L^{c3} \epsilon \ell_L^3\, S_1 + \lambda_R^{c\tau}\, \bar{c}_R^c \tau_R\, S_1$$



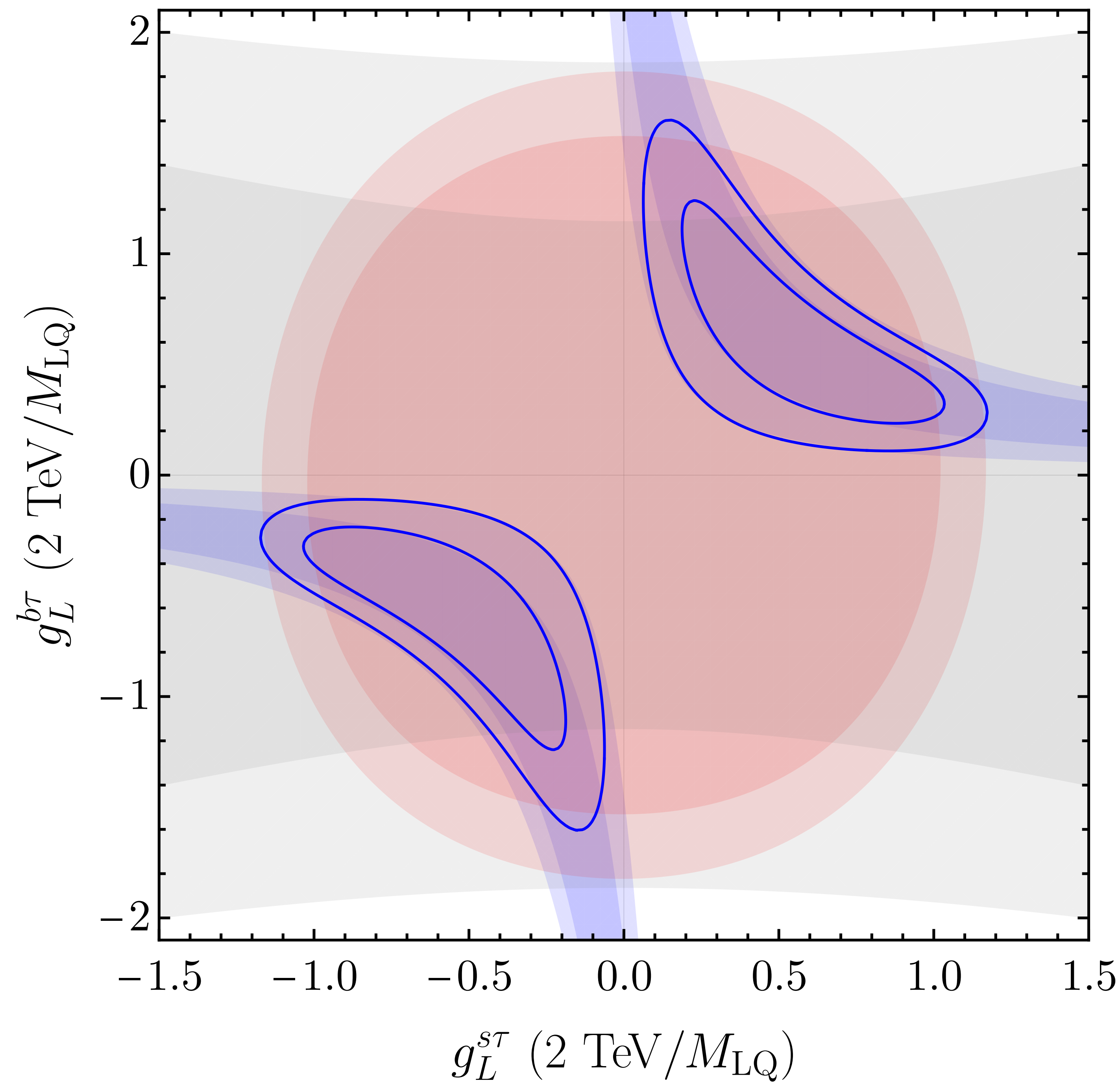
Simplified R_2 scalar LQ model and fit

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

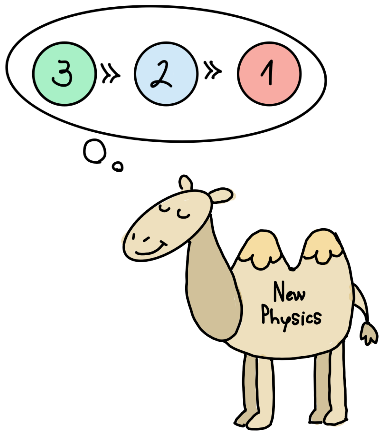


Simplified U_1 vector LQ model and fit

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

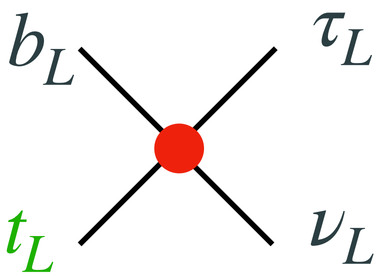


U(2)-like new physics in $b \to c\tau\nu$ decays



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

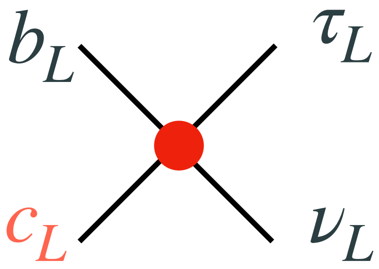
Flavor conserving



$$\mathscr{A}_{\rm NP}^{33} \sim \frac{1}{\Lambda_{\rm NP}^2}$$

$+$

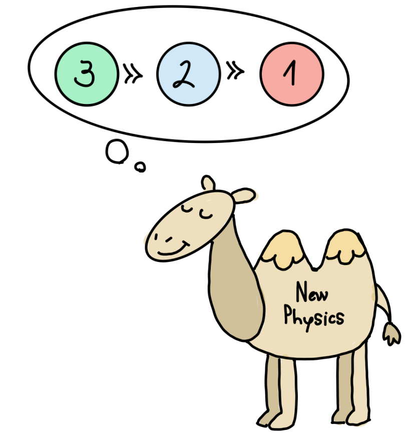
Flavor violating



$$\mathscr{A}_{\rm NP}^{23} \sim \frac{V_q}{\Lambda_{\rm NP}^2}$$

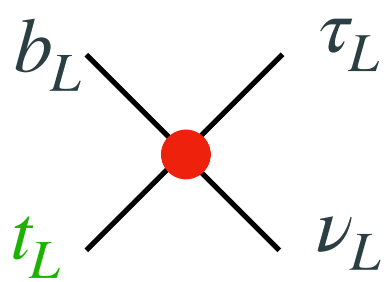
$$\mathscr{A}_{\rm NP}(b \to c\tau\nu) = V_{cb}\mathscr{A}_{\rm NP}^{33} + V_{cs}\mathscr{A}_{\rm NP}^{23}$$

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



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

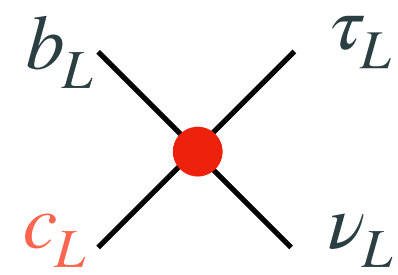
Flavor conserving



$$\mathscr{A}_{\rm NP}^{33} \sim \frac{1}{\Lambda_{\rm NP}^2}$$

$+$

Flavor violating



$$\mathscr{A}_{\rm NP}^{23} \sim \frac{V_q}{\Lambda_{\rm NP}^2}$$

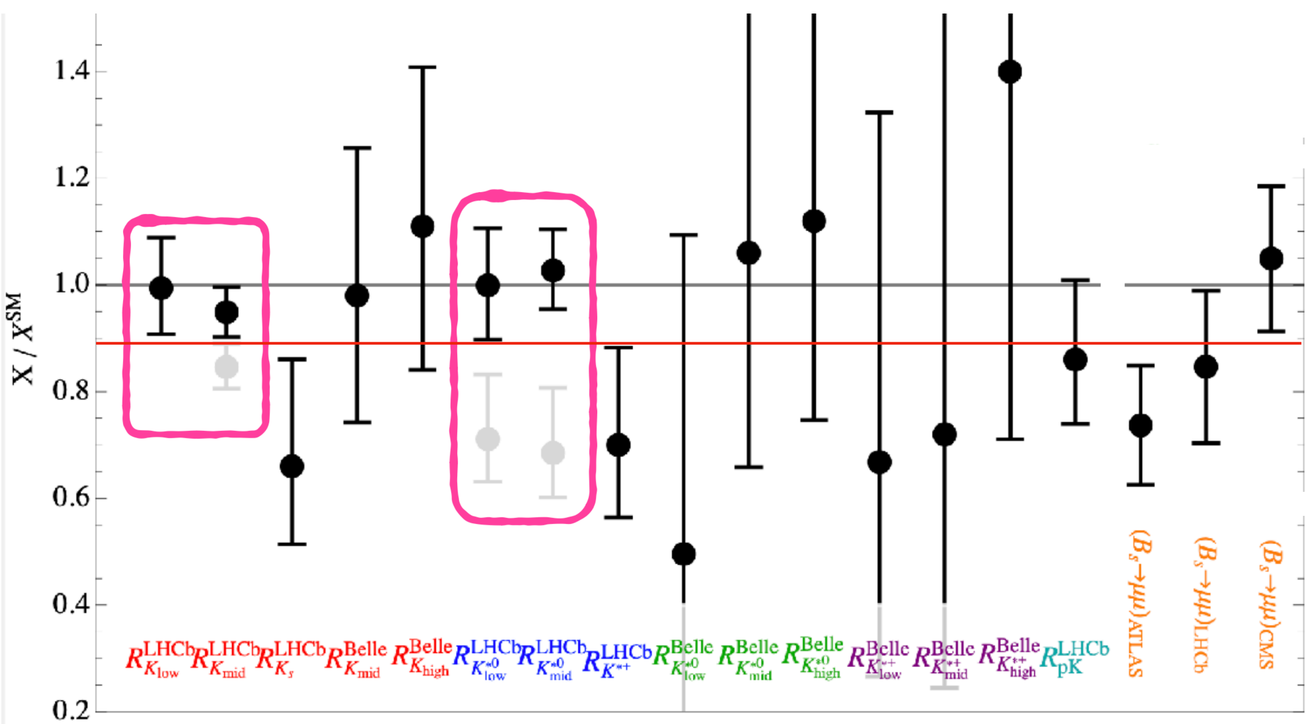
$$\mathscr{A}_{\rm NP}(b \to c\tau\nu) = V_{cb}\mathscr{A}_{\rm NP}^{33} + V_{cs}\mathscr{A}_{\rm NP}^{23}$$

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

$$2\frac{\mathscr{A}_{\rm NP}}{\mathscr{A}_{\rm SM}} \approx \frac{v^2}{\Lambda_{\rm NP}^2}\left(1 + \frac{V_q}{V_{cb}}\right) \approx \delta R_{D*} \quad \underset{(V_q = 0.1)}{\Longrightarrow} \quad \Lambda_{\rm NP} \approx 1.3 \text{ TeV} \left(\frac{0.12}{\delta R_{D*}}\right)^{1/2}$$

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

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



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

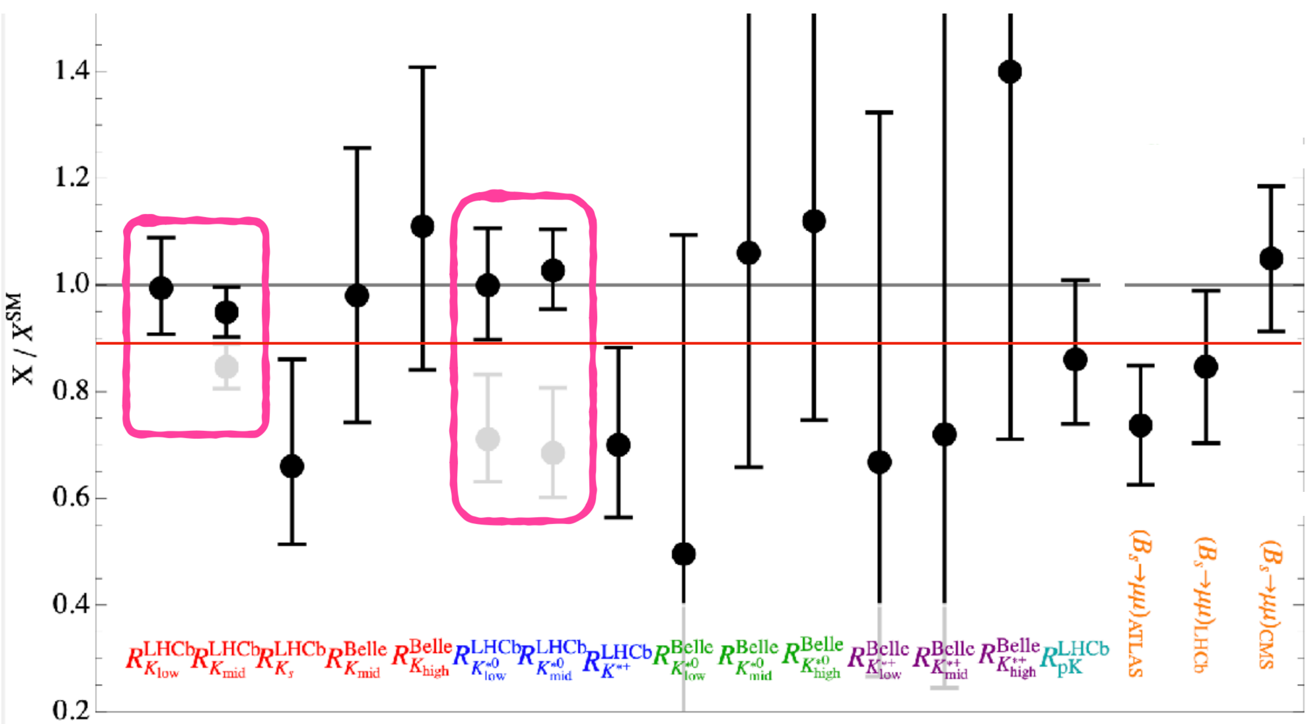
$$\text{low-}q^2 \begin{cases} R_K &= 0.994\ ^{+0.090}_{-0.082}\,(\text{stat})^{+0.029}_{-0.027}\,(\text{syst}), \\ R_{K^*} &= 0.927\ ^{+0.093}_{-0.087}\,(\text{stat})^{+0.036}_{-0.035}\,(\text{syst}), \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K &= 0.949\ ^{+0.042}_{-0.041}\,(\text{stat})^{+0.022}_{-0.022}\,(\text{syst}), \\ R_{K^*} &= 1.027\ ^{+0.072}_{-0.068}\,(\text{stat})^{+0.027}_{-0.026}\,(\text{syst}). \end{cases}$$

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

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

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



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

$$\text{low-}q^2 \begin{cases} R_K &= 0.994\ ^{+0.090}_{-0.082}\,(\text{stat})^{+0.029}_{-0.027}\,(\text{syst}), \\ R_{K^*} &= 0.927\ ^{+0.093}_{-0.087}\,(\text{stat})^{+0.036}_{-0.035}\,(\text{syst}), \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K &= 0.949\ ^{+0.042}_{-0.041}\,(\text{stat})^{+0.022}_{-0.022}\,(\text{syst}), \\ R_{K^*} &= 1.027\ ^{+0.072}_{-0.068}\,(\text{stat})^{+0.027}_{-0.026}\,(\text{syst}). \end{cases}$$

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

U(2)-breaking parameter:

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

Nothing changes here, still calls for light NP!

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

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

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