

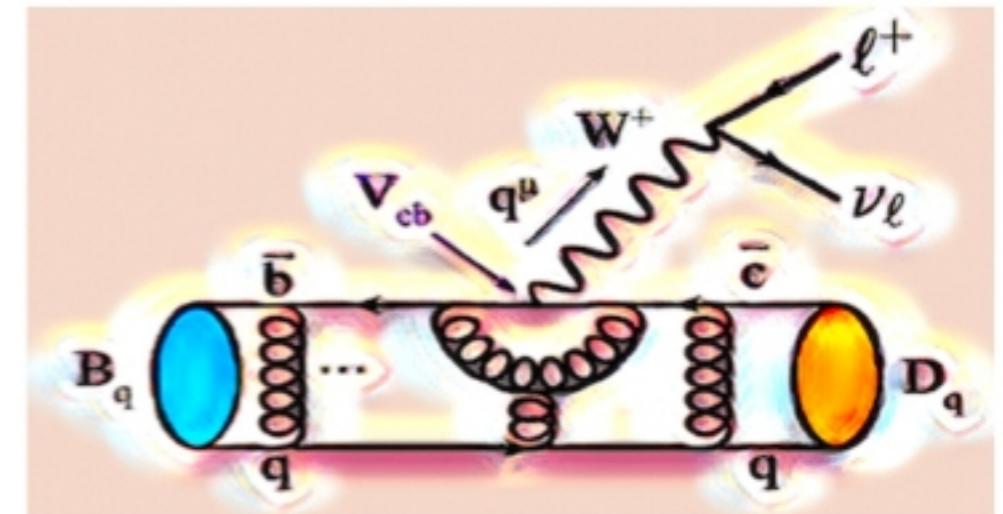


University of
Zurich^{UZH}

Mostly Leptoquarks and some VL Fermions

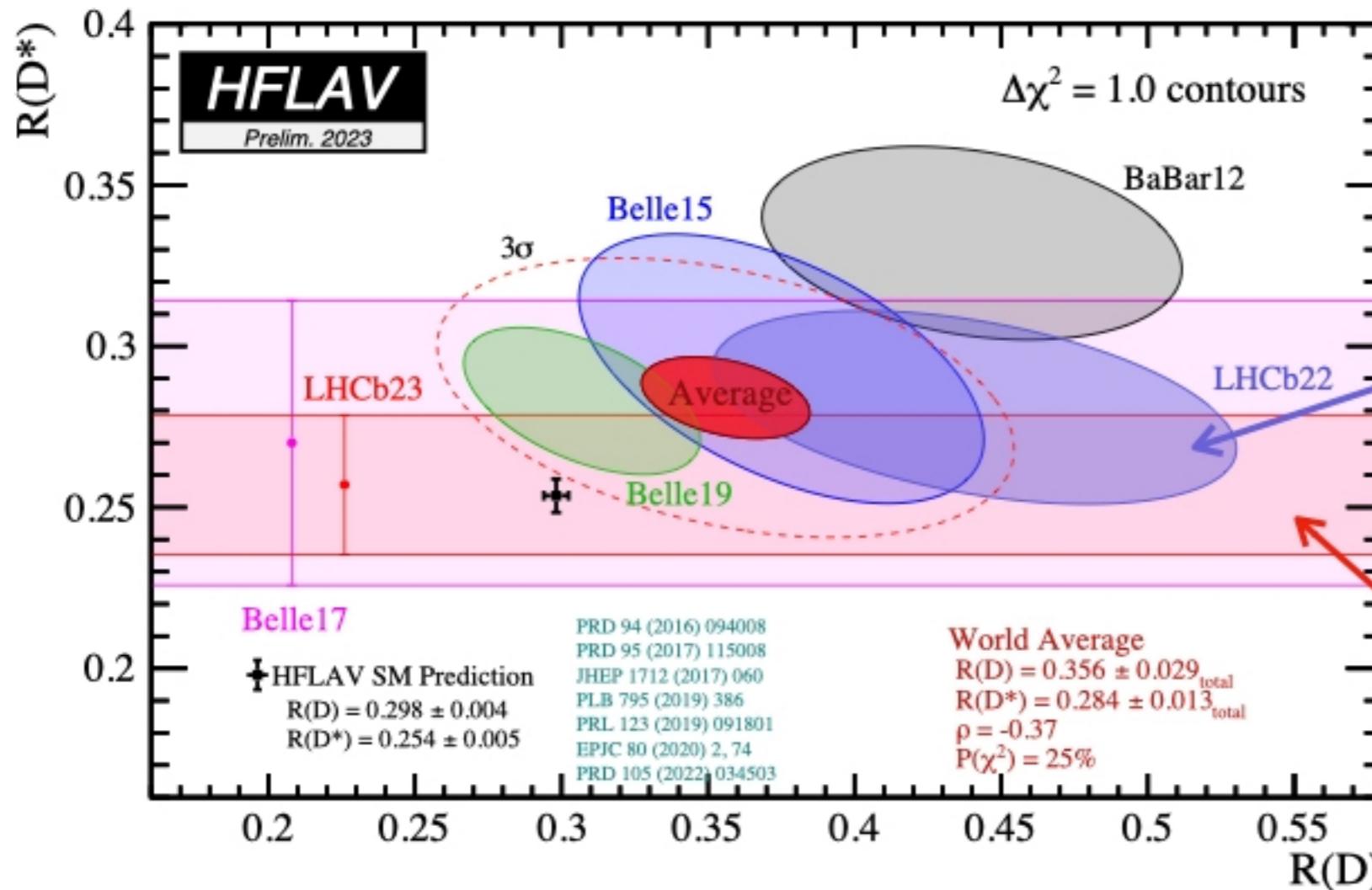
Ben A. Stefanek

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University of Zurich



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

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](#)]

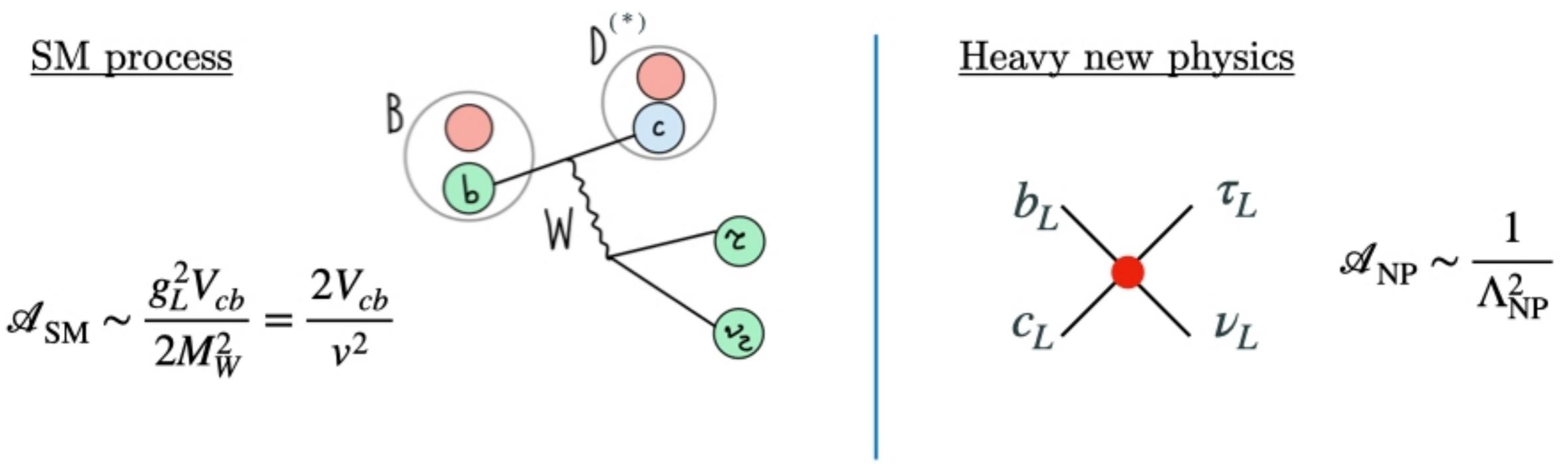
New! 2023 LHCb $\tau \rightarrow$ had: R_{D^*} with Run 1 + partial Run 2 data. Hadronic taus.

- 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, 3.2σ 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

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

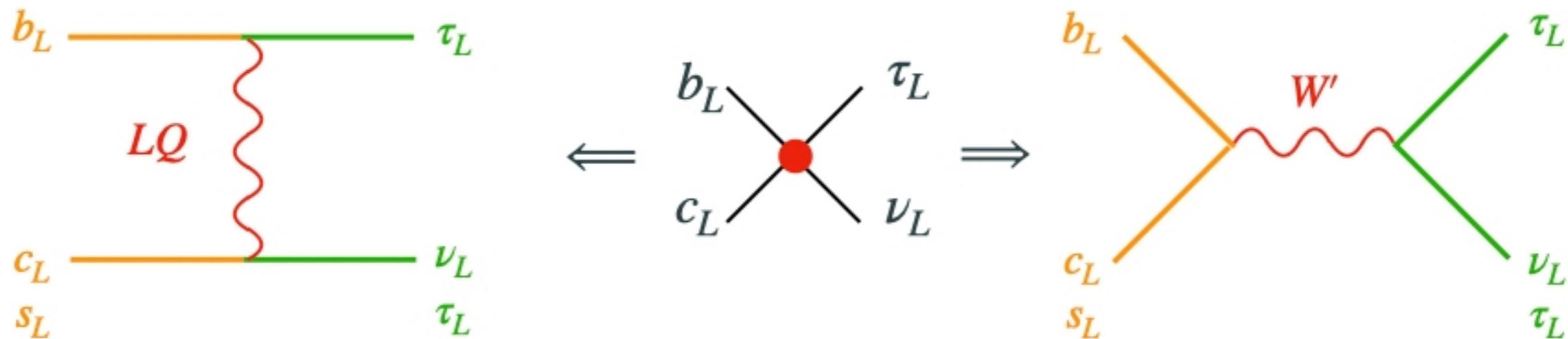
- We need $\sim 10\%$ of a tree-level SM process due to NP. Heavy NP should therefore also be tree-level to compete. Consider Fermi-like LH NP:



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

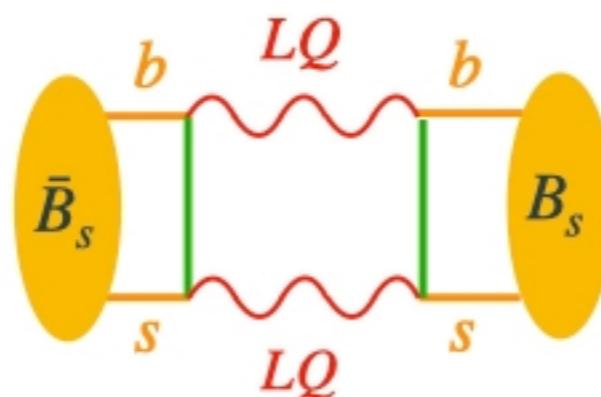
$$2 \frac{\mathcal{A}_{\text{NP}}}{\mathcal{A}_{\text{SM}}} = \frac{v^2}{V_{cb} \Lambda_{\text{NP}}^2} \approx \delta R_{D^*} \implies \Lambda_{\text{NP}} \approx \frac{v}{\sqrt{V_{cb} \delta R_{D^*}}} \approx 3.6 \text{ TeV} \left(\frac{0.12}{\delta R_{D^*}} \right)^{1/2}$$

What kind of new particles could we have?

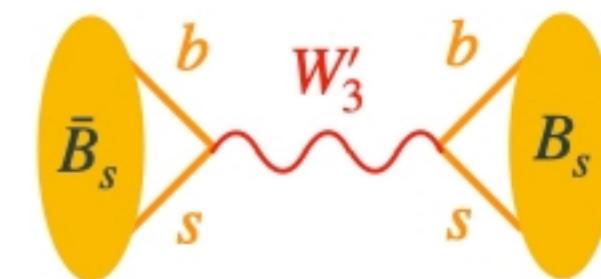


- LH NP $\Rightarrow b \rightarrow s\tau\tau(\nu\nu)$ couplings. LQ's have two important advantages

1. $\Delta F = 2$:

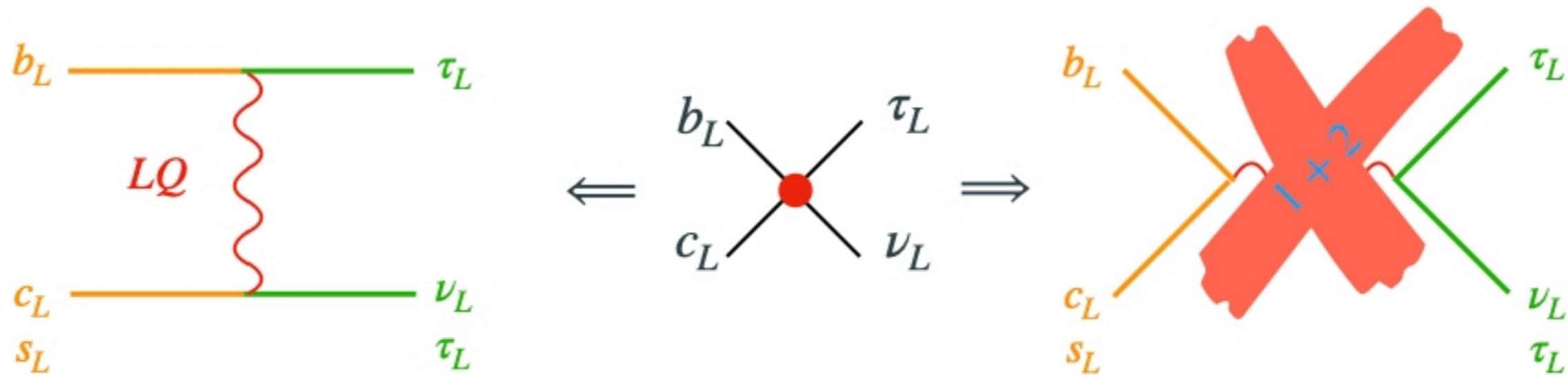


vs



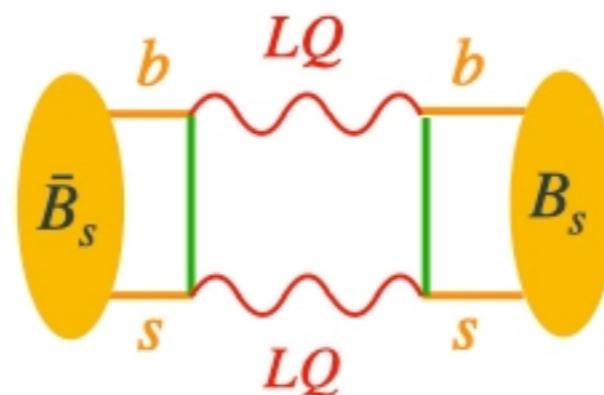
2. **Direct searches:** t-channel versus resonant s-channel production

Only leptoquarks are viable mediators!

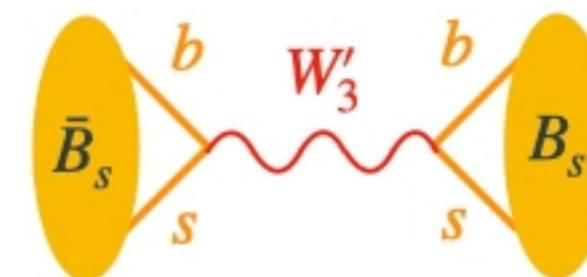


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vs



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

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, Bećirević, 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](#), ...]

★ $R_2 \sim (3, 2, 7/6)$

[Bećirević 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:

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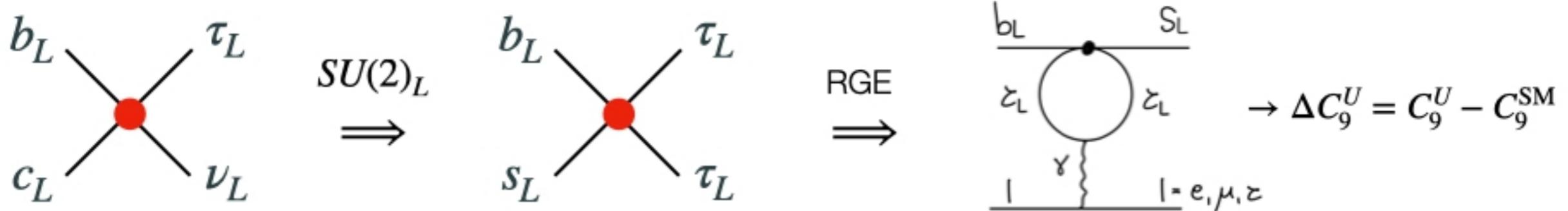
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Scalar Leptoquarks:

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

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



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

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 $\sim O(V_{cb})$

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

 **RUNNING to EW SCALE + MATCHING** 

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

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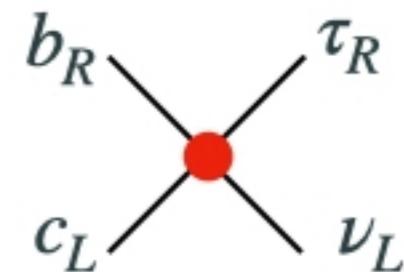
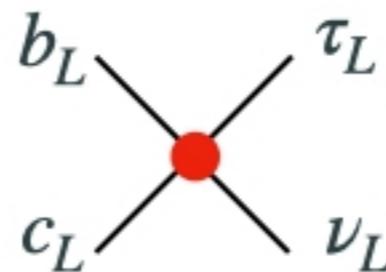
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Contact interaction:

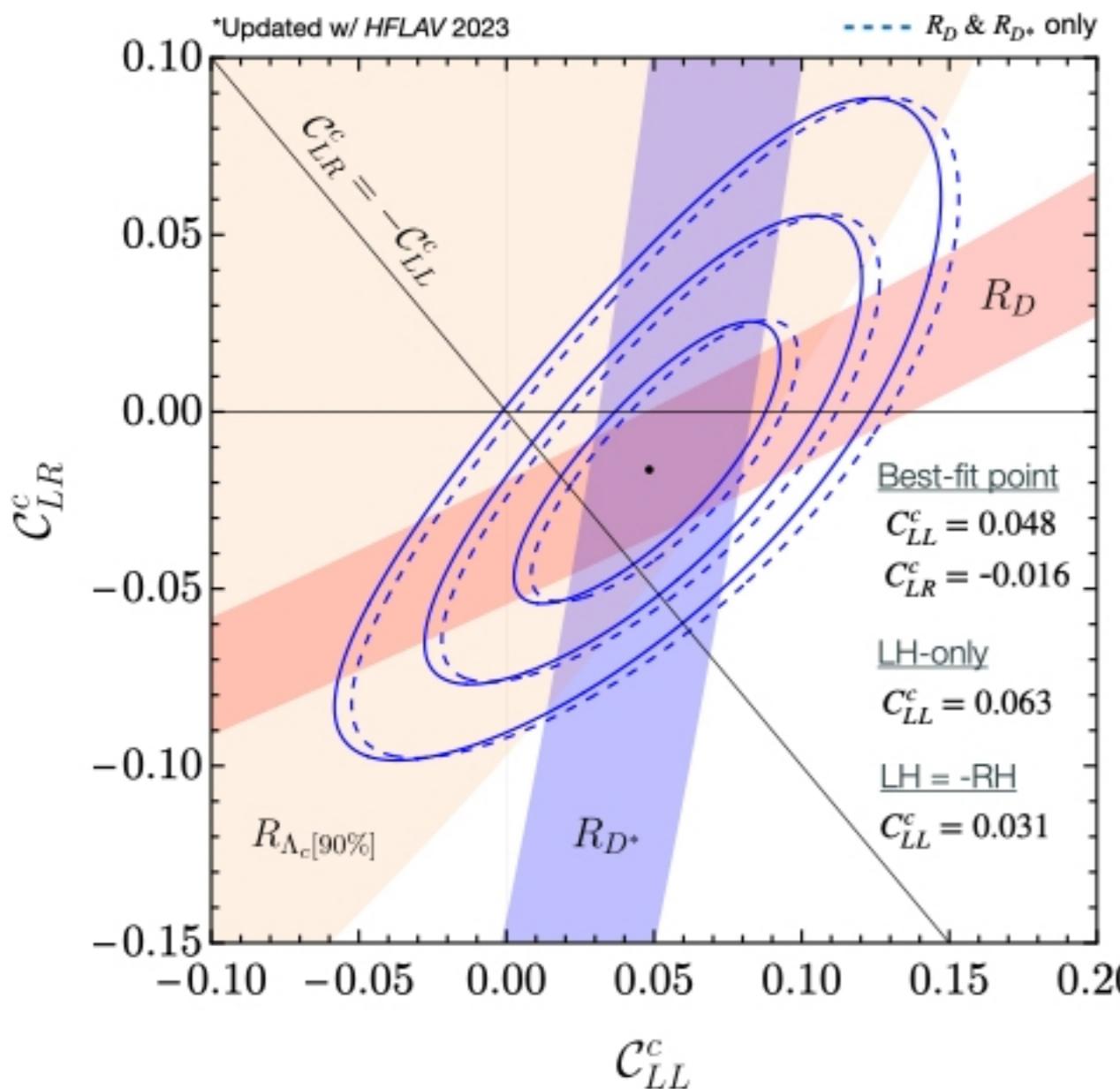


Low-energy WC's \leftrightarrow Model parameters:

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

Low-energy fit for U_1 leptoquark model $U_1 \sim (3, 1, 2/3)$

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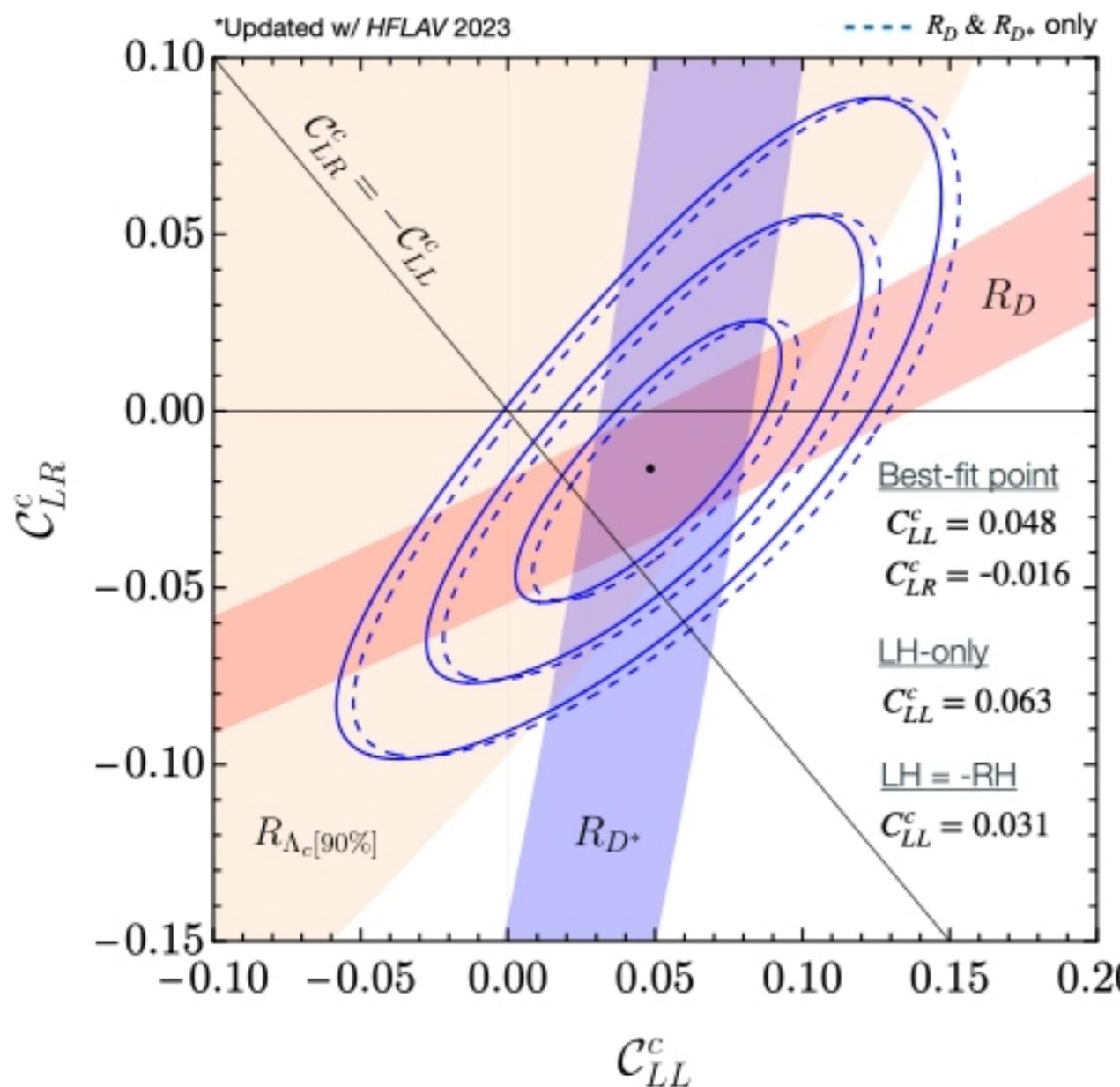
$$\delta R_{D^{(*)}} \approx 2C_{LL}^c - a_{D^{(*)}} C_{LR}^c \quad \begin{cases} a_D \approx 3.00 \\ a_{D^*} \approx 0.24 \end{cases}$$

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Matching: NP scale and U(2)-breaking

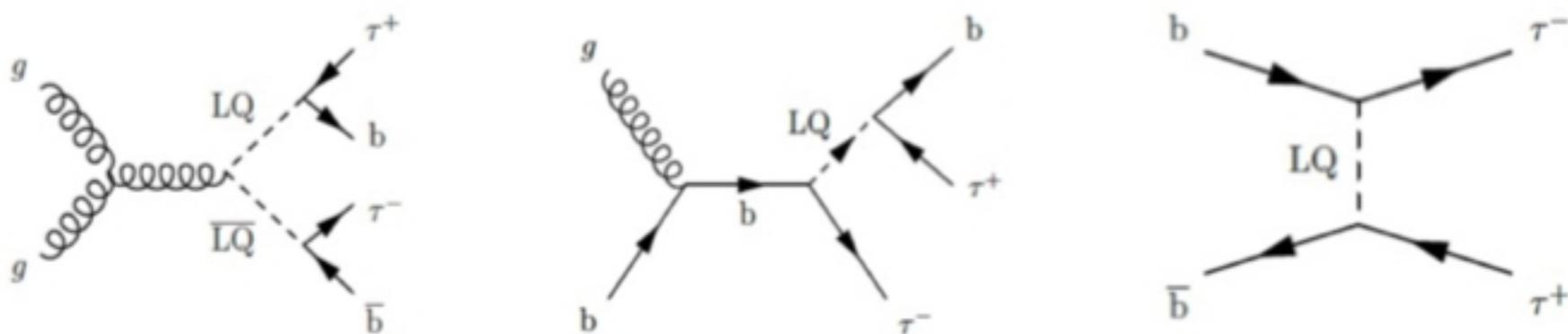
$$\frac{1}{\Lambda_{\text{NP}}^2} = \frac{g_U^2}{2M_U^2}, \quad V_q = \beta_L^{s\tau}$$

New physics scale preferred by low-energy fit:

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

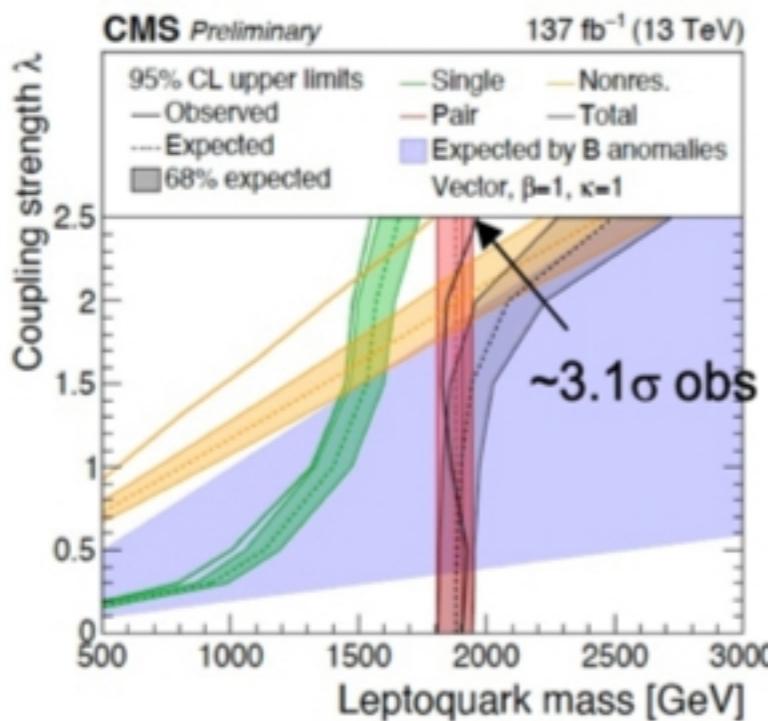
{LH-only, BFP, LH=-RH}

High-energy searches: U_1 leptoquark

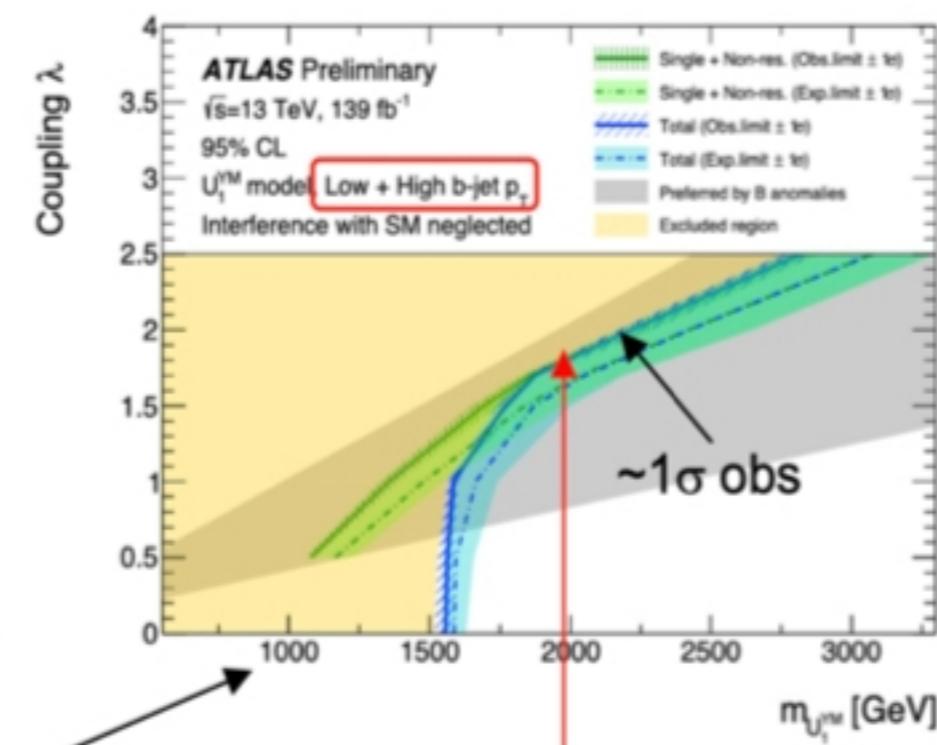


Caveat: BR=1 (CMS) vs BR=0.5 (ATLAS)

[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:

$$U(1)_Y$$

$$\boxed{SU(4)_h \times SU(3)_l \times SU(2)_L \times U(1)_{l+R}} \xrightarrow{\langle \Omega_{1,3,15} \rangle \sim \mathcal{O}(\text{TeV})} SU(3)_c \times SU(2)_L \times U(1)_Y + \mathbf{U}_1, \mathbf{G}', \mathbf{Z}'$$

$SU(3)_c$

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

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$$SU(3)_c$$

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](#)]

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

UV Model: The origin of light-heavy CKM mixing

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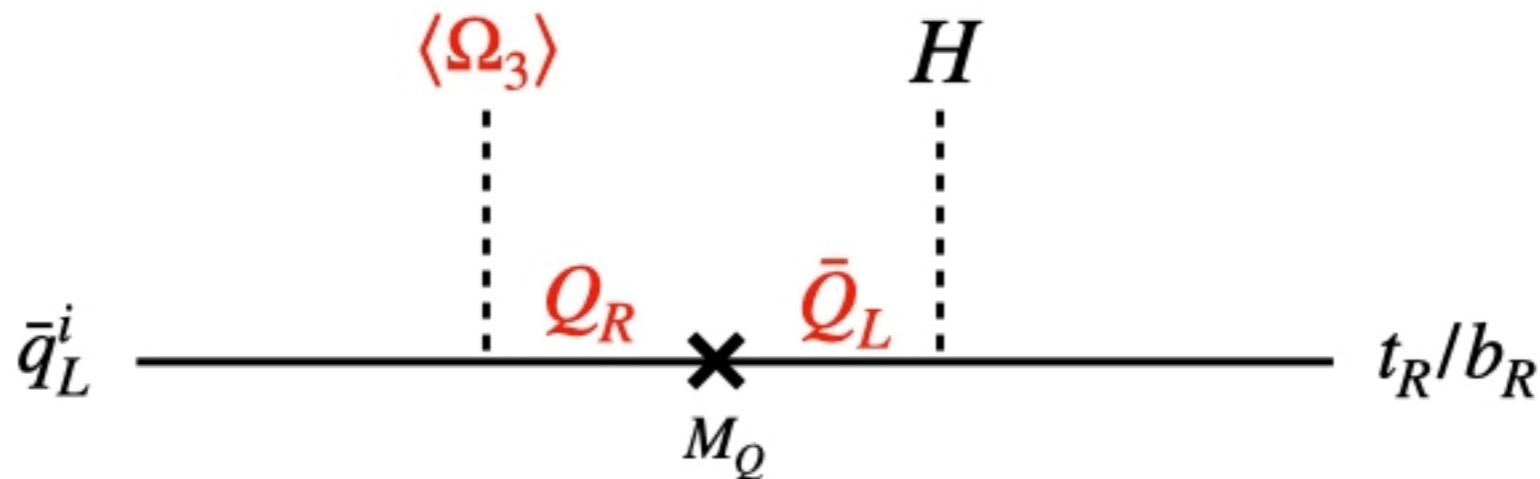
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$$\chi_{L,R} \sim \begin{pmatrix} Q_{L,R} \\ L_{L,R} \end{pmatrix}$$

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

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



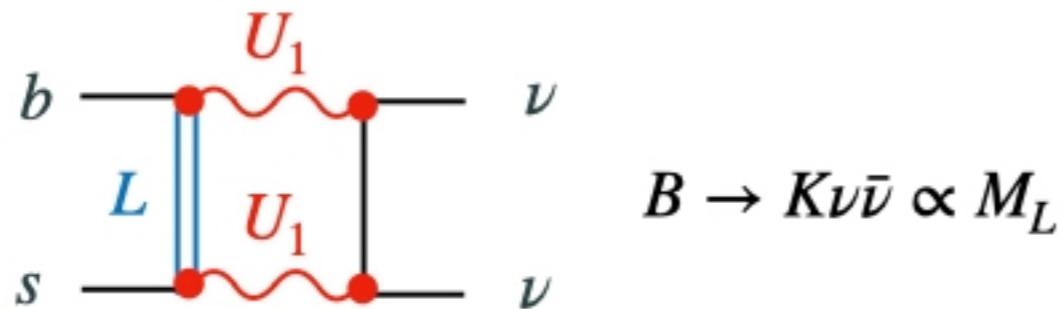
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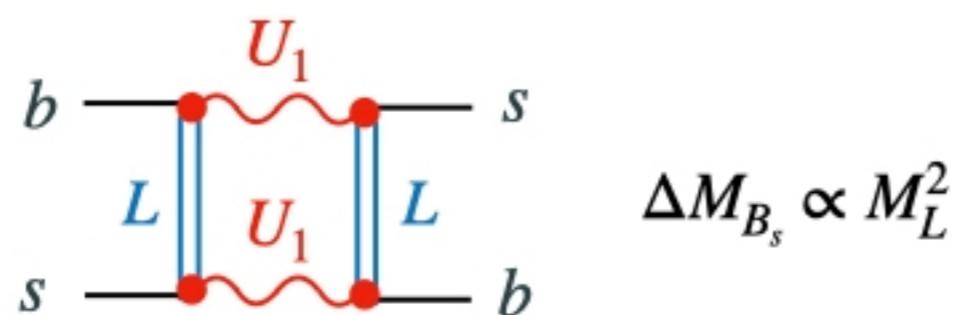
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Vector-like Lepton:

- Controls loop FCNC's



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



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

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

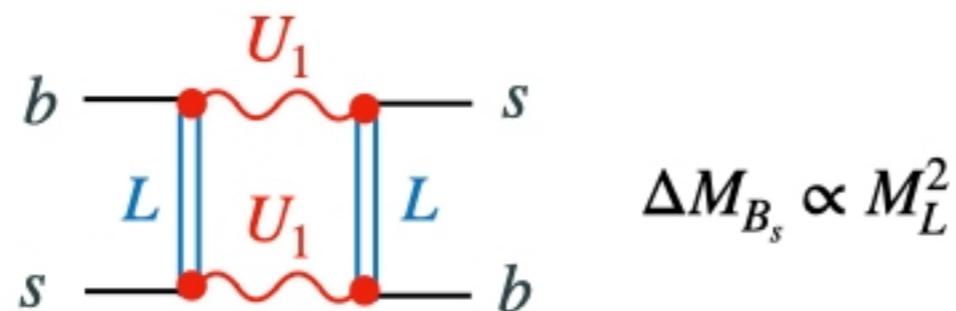
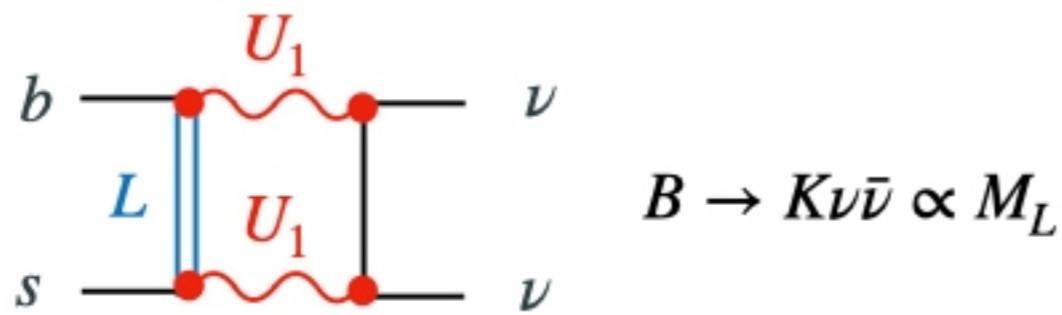
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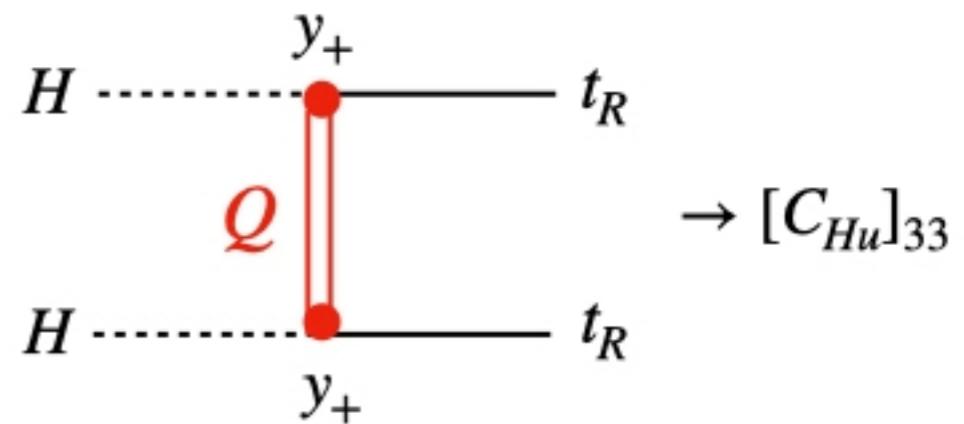


[CMS-PAS-B2G-21-004]: $M_L \gtrsim 500 \text{ GeV}$

Vector-like Quark:

- CKM mixing and effects in EWPO via RGE

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



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

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.

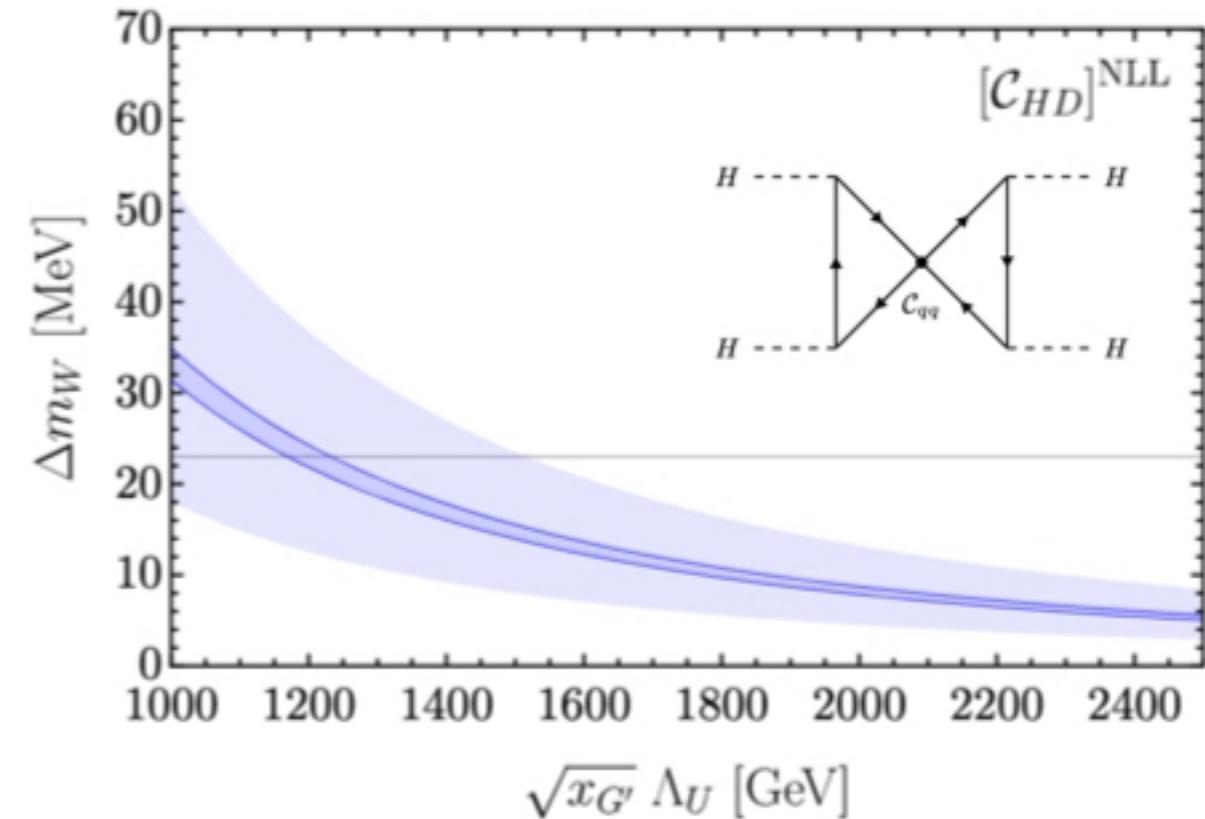
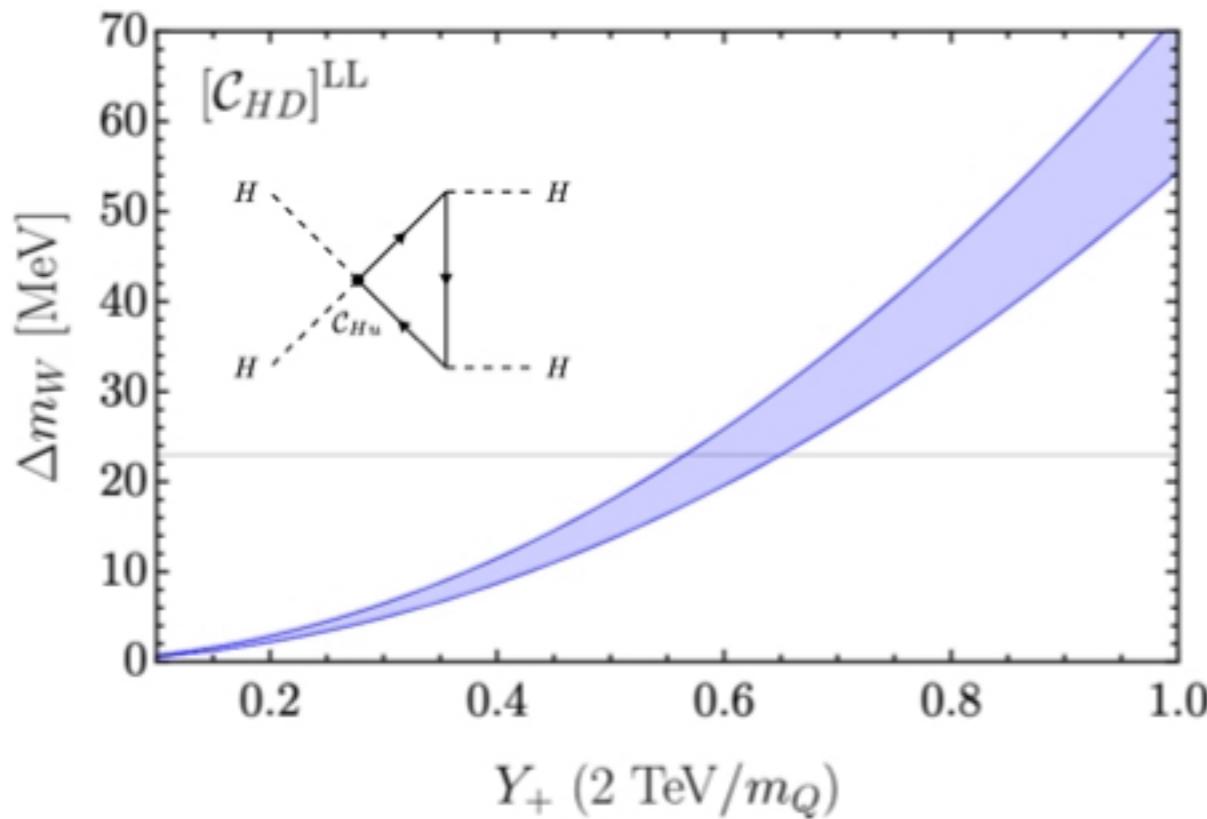
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- In addition to the U_1 LQ, we also get neutral G' , Z' vectors.
- We also need a vector-like quark and lepton Q, L for fermion mixing.
- New colored states Q, G' give sizable shifts in the W-mass via RGE effects.

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

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

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



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

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 $b \rightarrow c\tau\nu$ 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 $b \rightarrow c\tau\nu$ transitions to flavor universal effects in the $b \rightarrow s\ell\ell$ 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 $B \rightarrow K\nu\bar{\nu}$ and large positive shifts to the W -mass via RGE.
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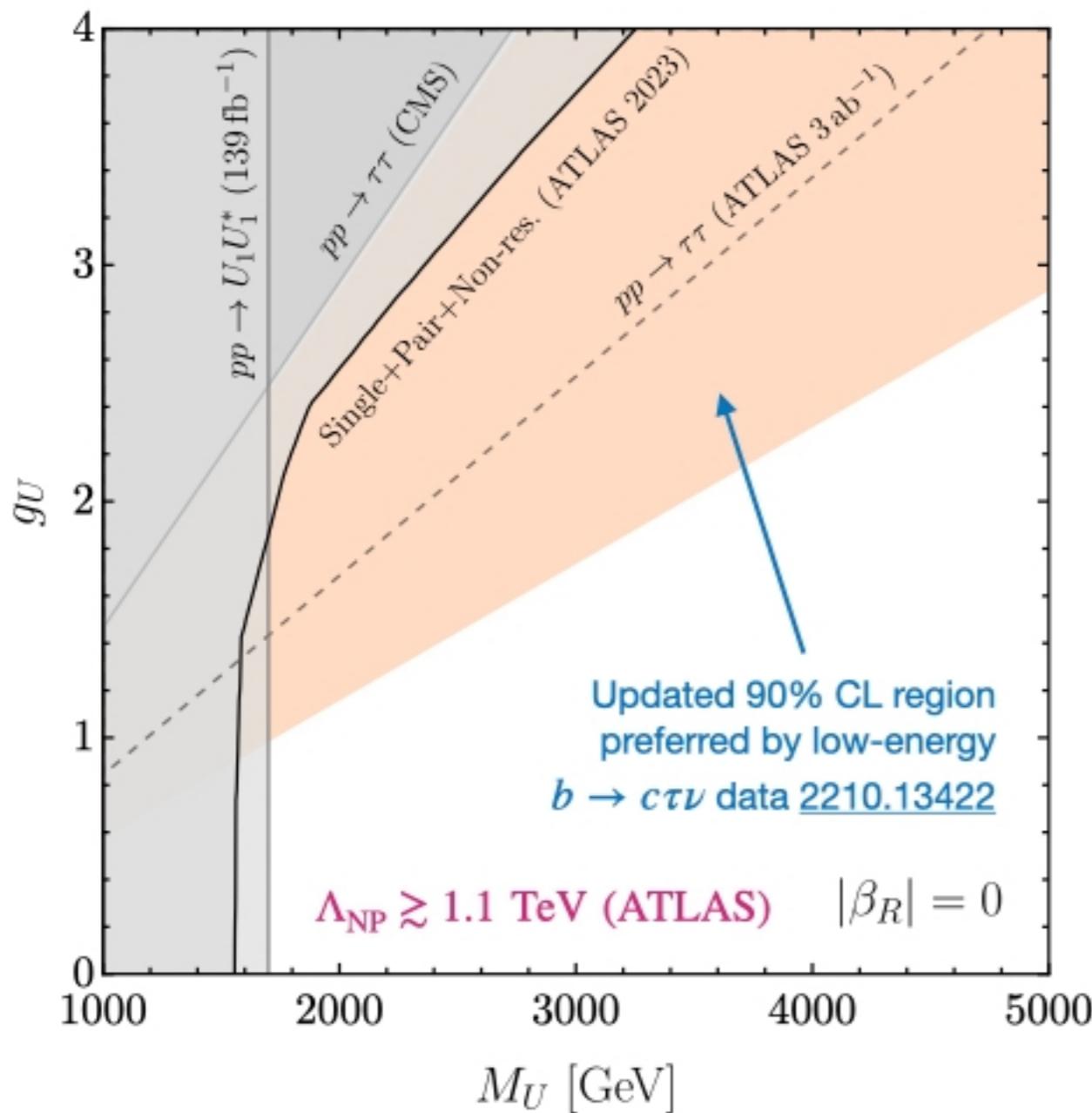
Thanks a lot for your attention!

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- The VLF's give new loop-level pheno correlated with $R_{D^{(*)}}$, such as an ~50% enhancement in $B \rightarrow K\nu\bar{\nu}$ 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!

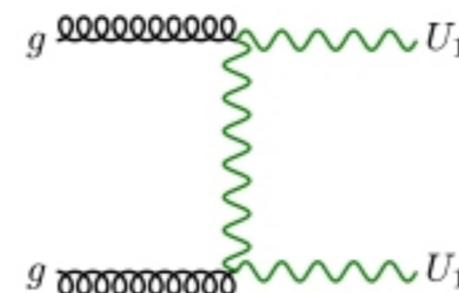
Backup Slides

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



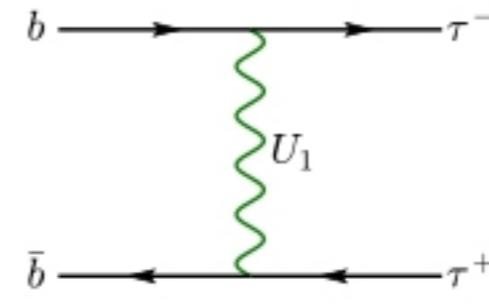
$$U_1 \rightarrow b\tau^+, t\bar{\nu}$$

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



2012.0417

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



2002.1222

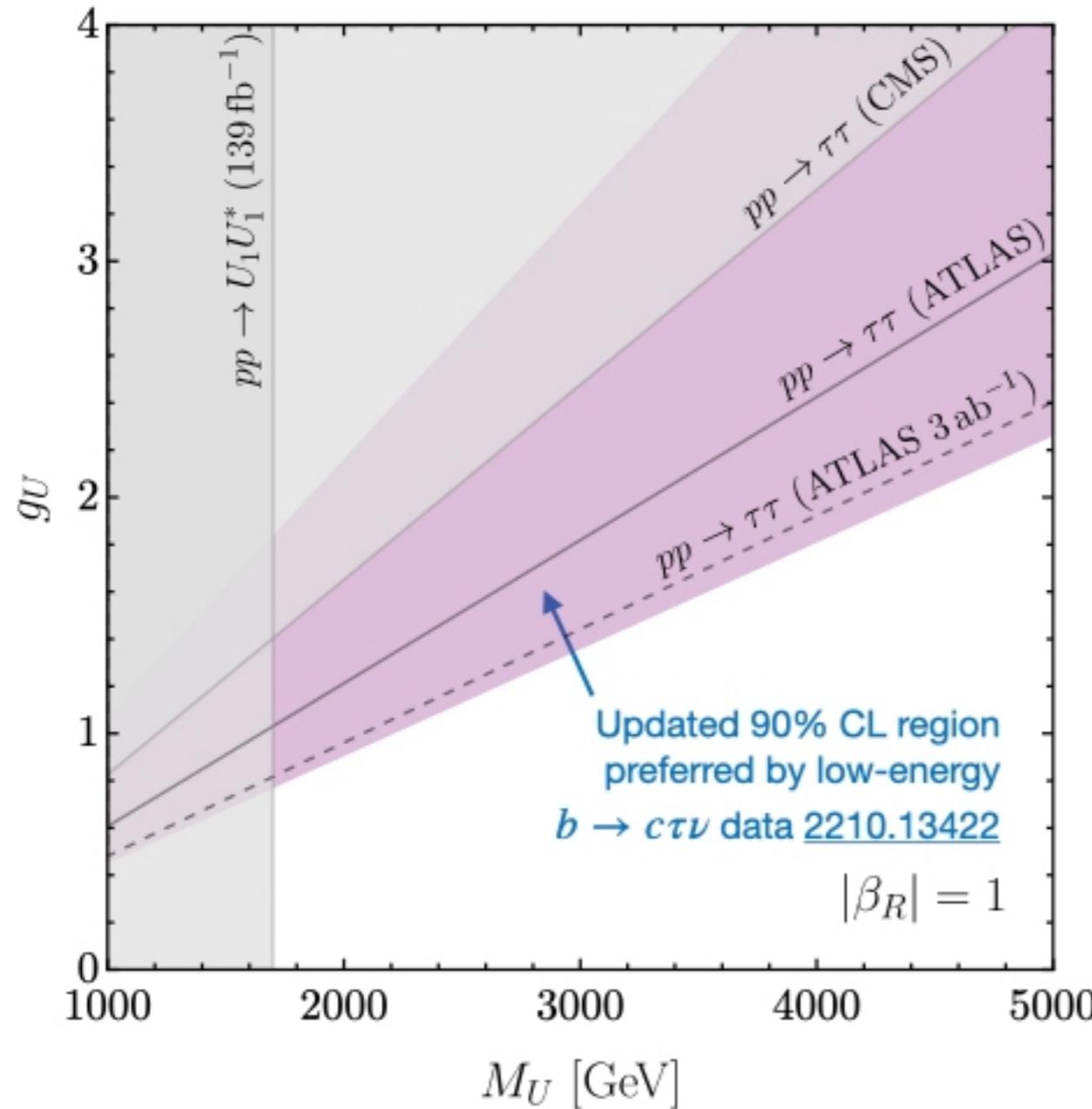
High mass Drell-Yan tails

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

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

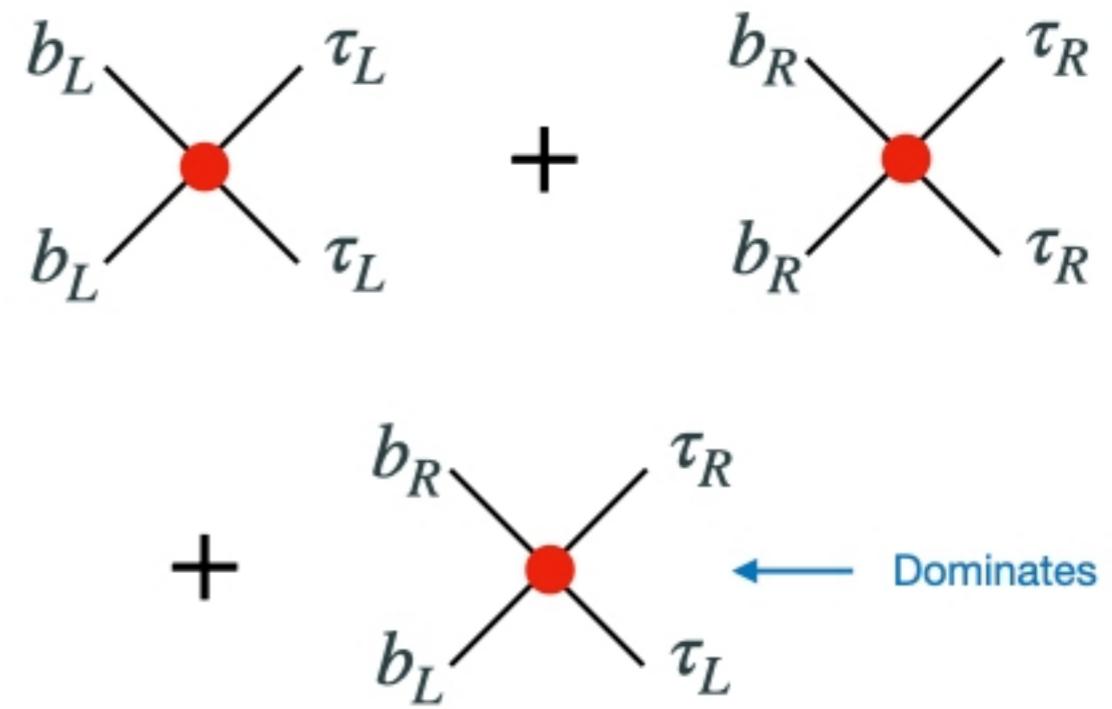
High-energy searches: U_1 leptoquark model (L&R)

- 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](#)]

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

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

SM

Vector LQ:

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



Scalar LQs:

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



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



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

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

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

- 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.

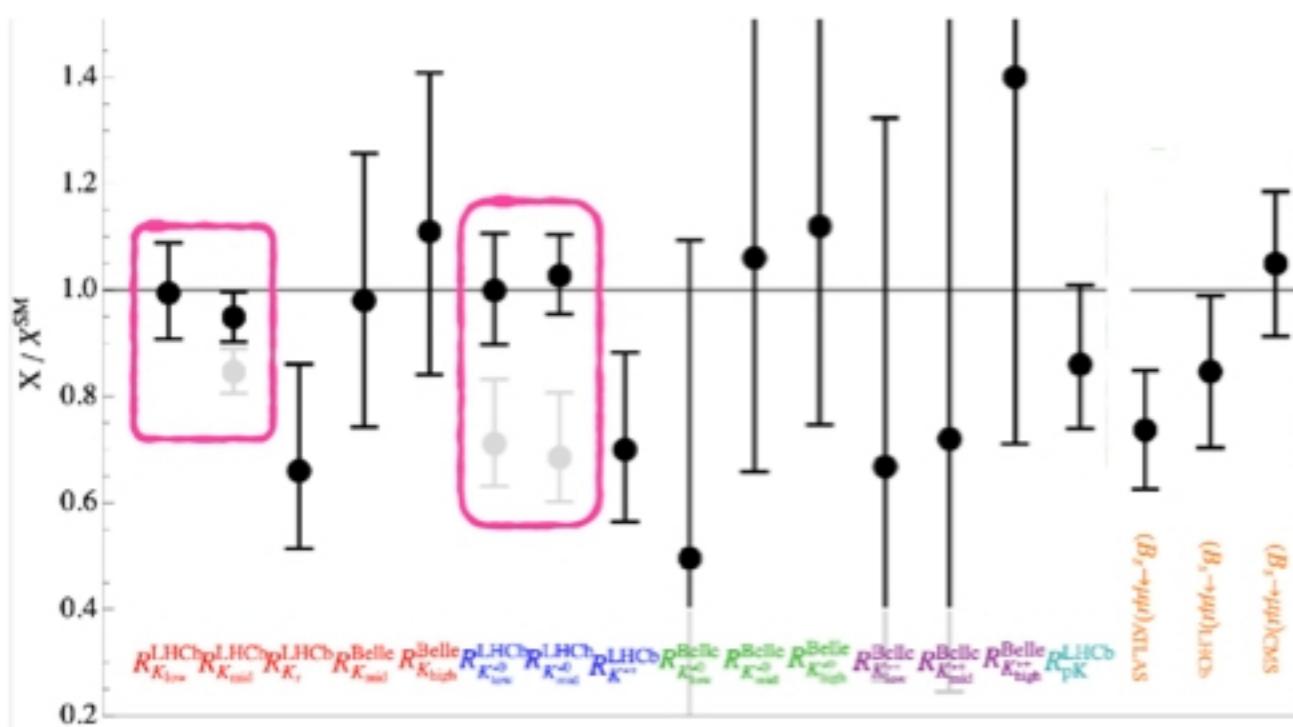
Neutral-current B-anomalies

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

- Until recently, two “types” of anomalies in $b \rightarrow sll$:
 1. μ/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 μ/e lepton flavor universality in $b \rightarrow s\ell\ell$ at $\sim 5\%$ level [LHCb,221209152]

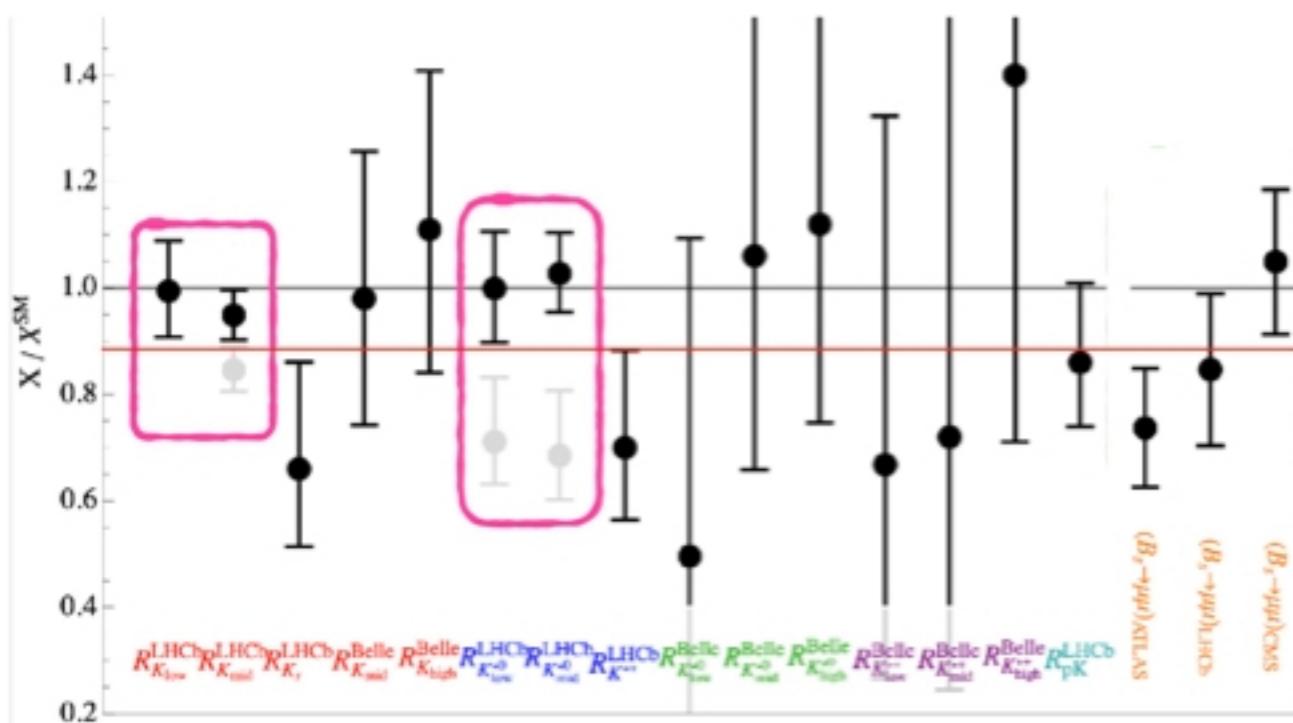


[compilation of $b \rightarrow s\mu\mu$ clean observables as of Dec. 2022 (©David Marzocca)]

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

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

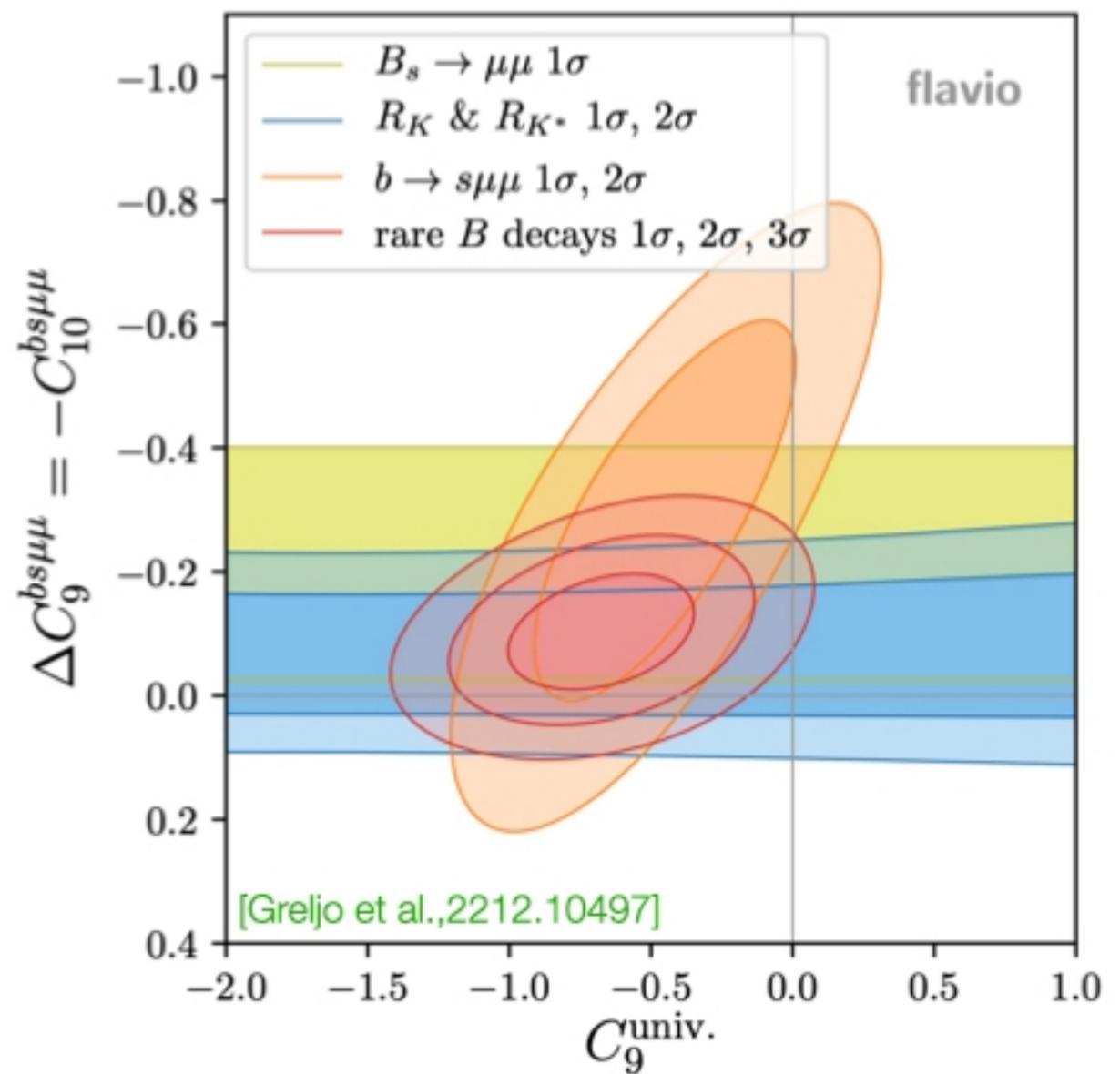
The $b \rightarrow s\ell\ell$ anomalies after

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

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

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

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



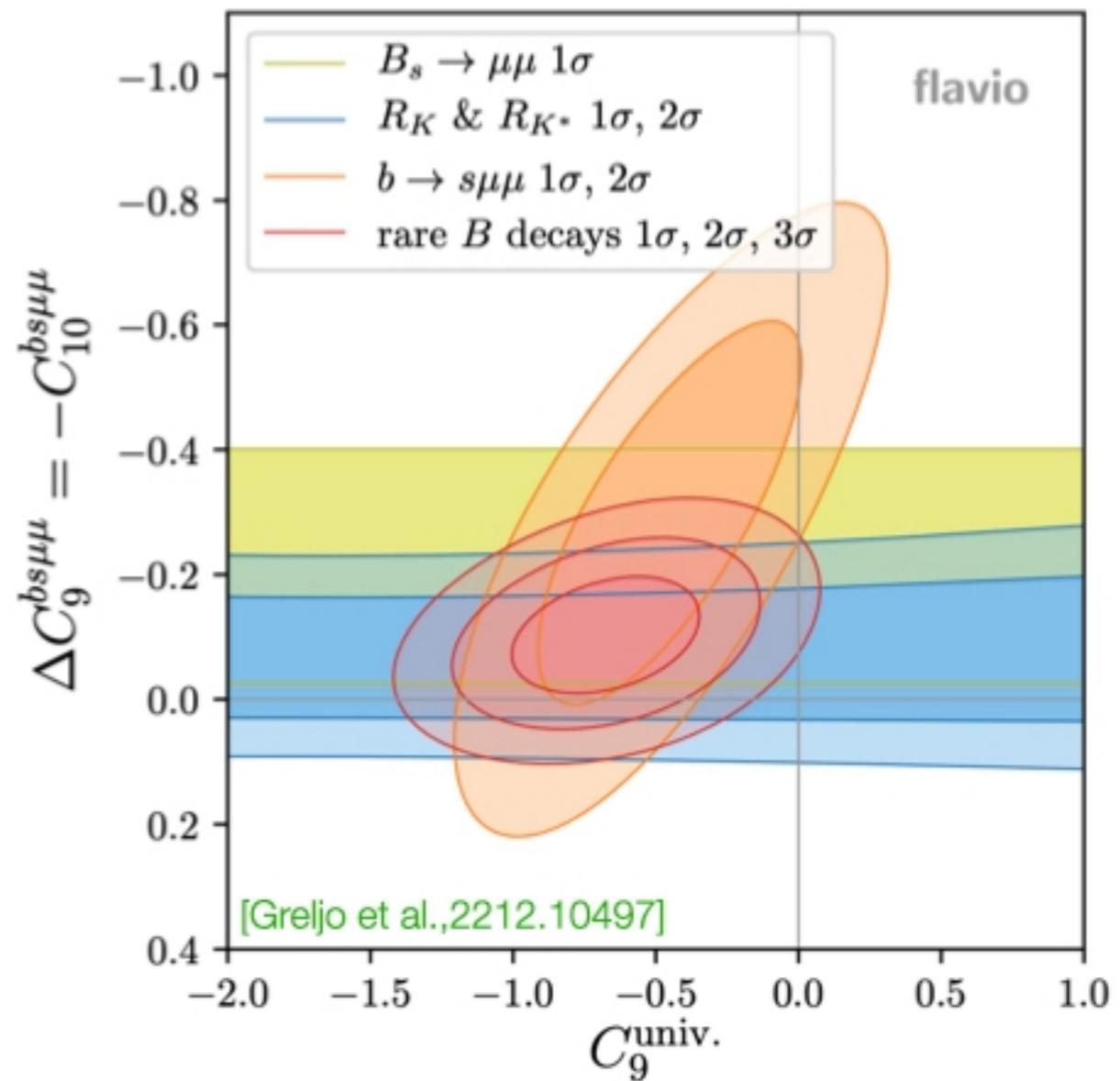
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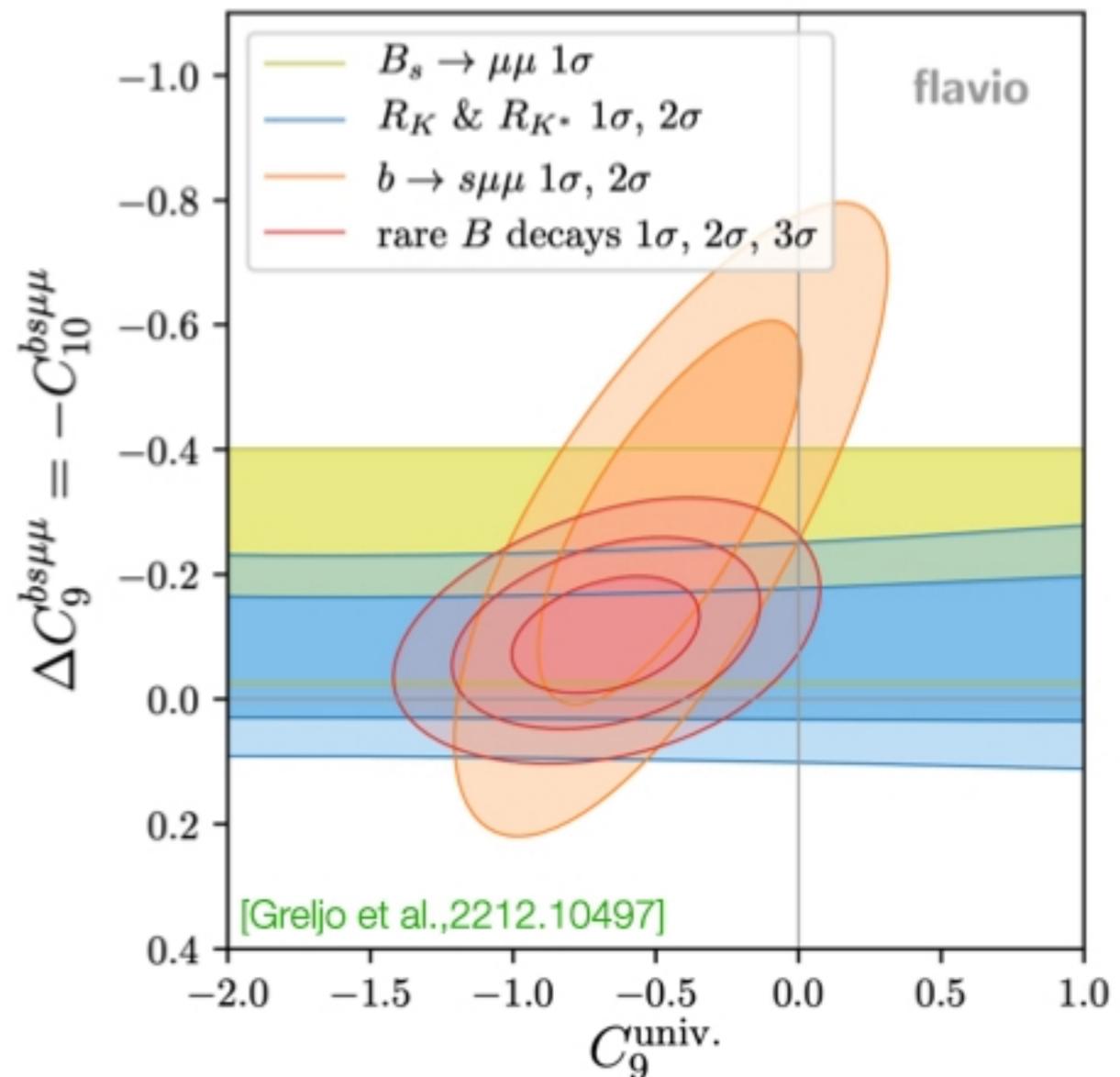
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* But, non-trivial to distinguish from long-distance QCD ("charming penguins")

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]



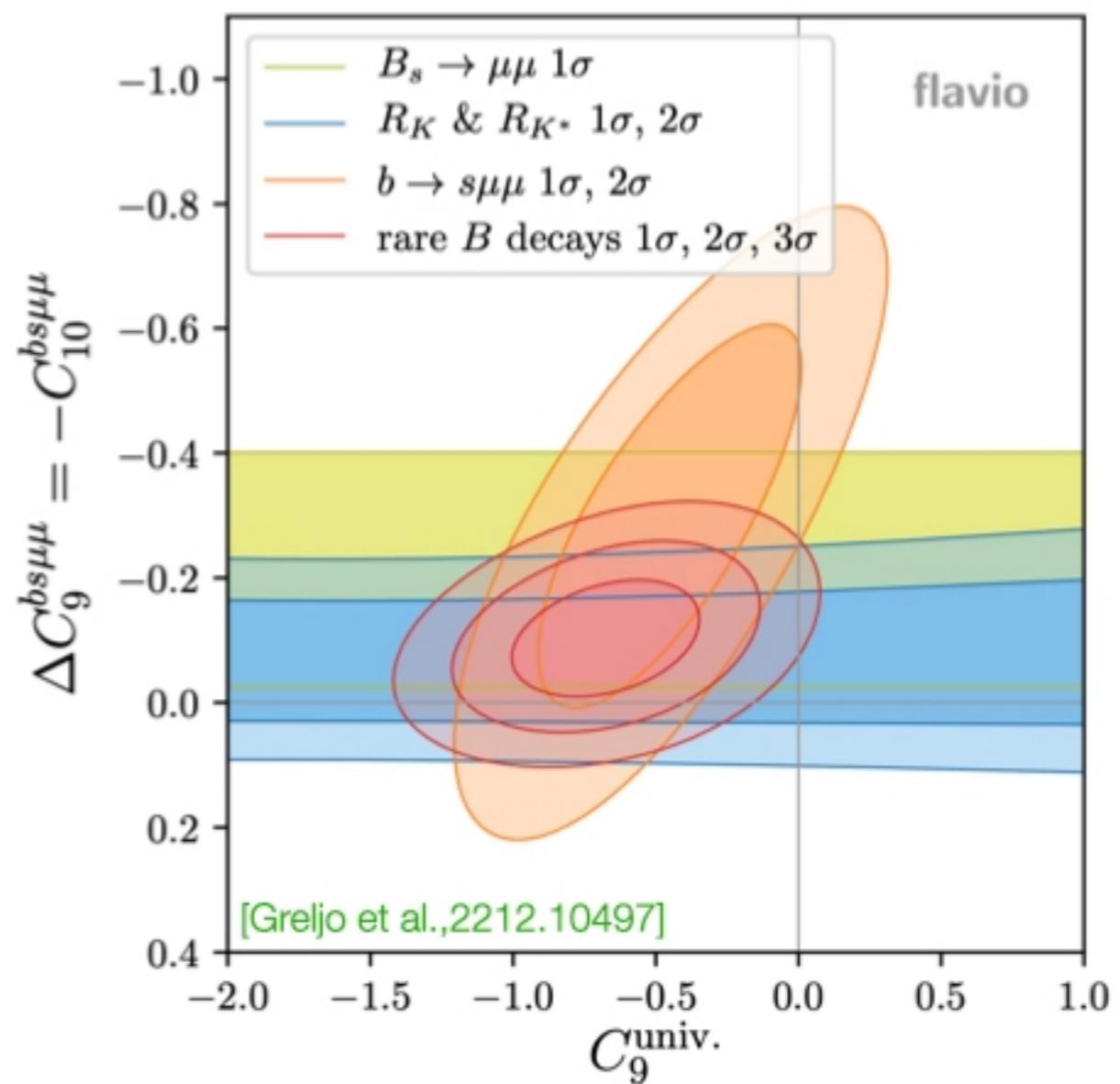
What changed? Implications for model building

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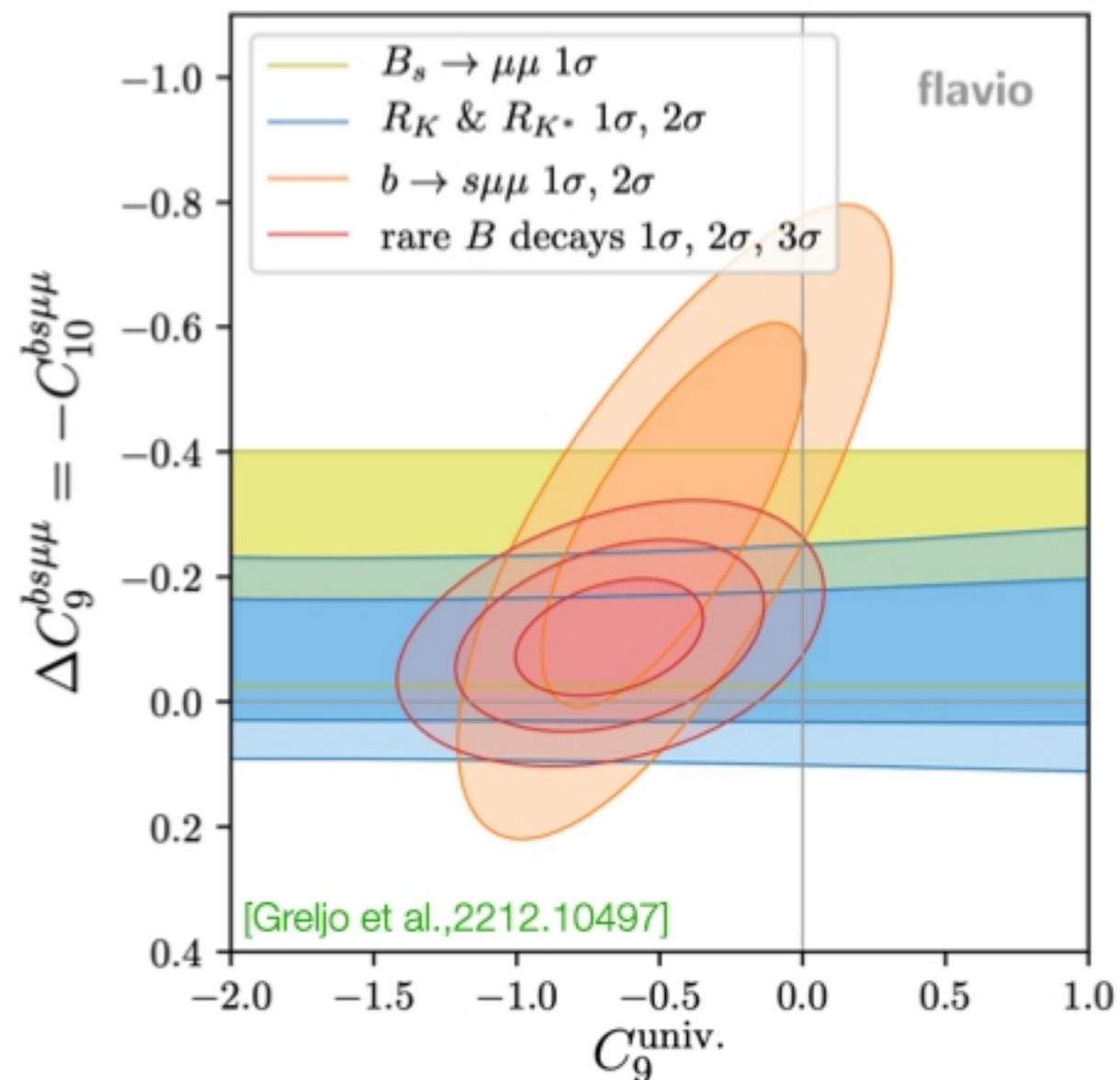
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- A flavor universal shift in C_9 is now sufficient to account for all $b \rightarrow s\mu\mu$ measurements.
- Old models for combined explanation of $R_{D^{(*)}}$ and $R_{K^{(*)}}$ now must be **μ/e universal at the $\sim 10\%$ level**. This is not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



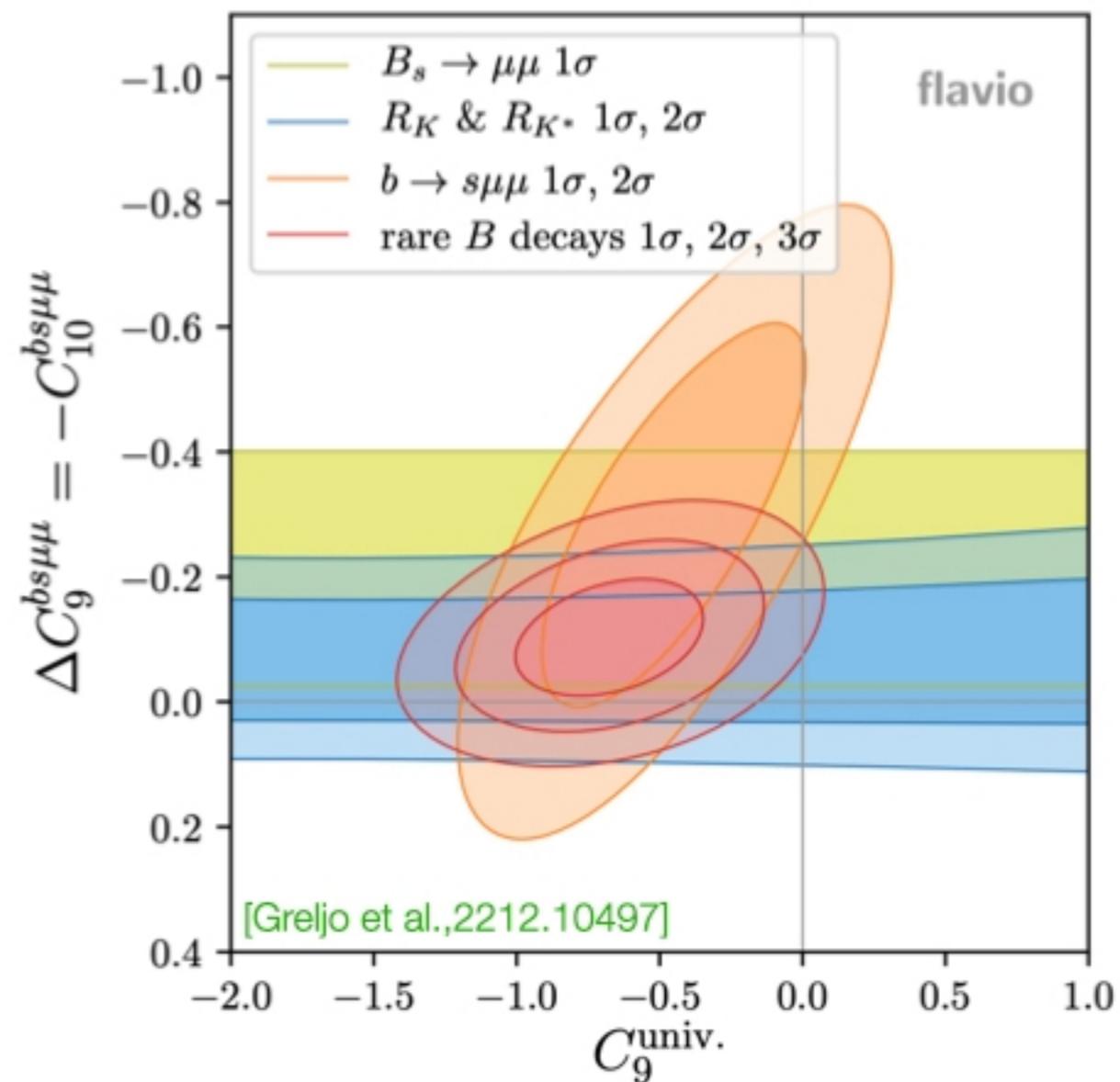
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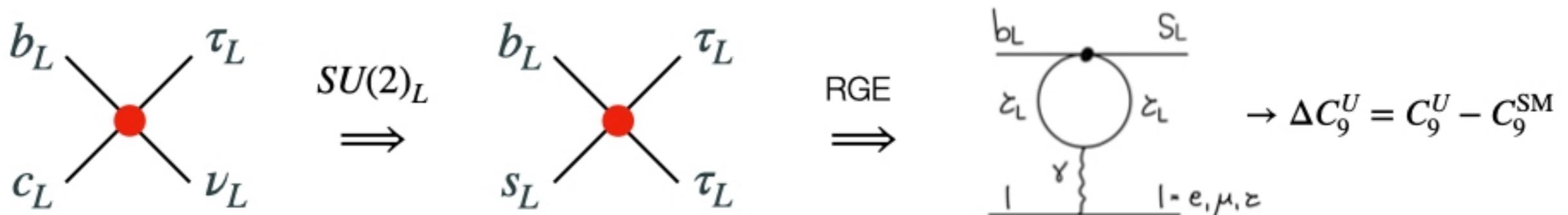
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- Still interesting to consider models for $R_{D^{(*)}}$ (unaffected) that also give flavor universal contributions to the $b \rightarrow s\ell\bar{\ell}$ system.



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:



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

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

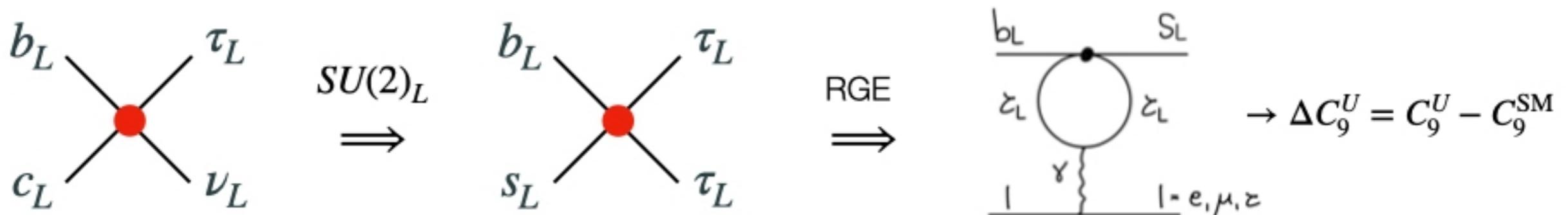
- Leading-log running in SM gauge couplings gives

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

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

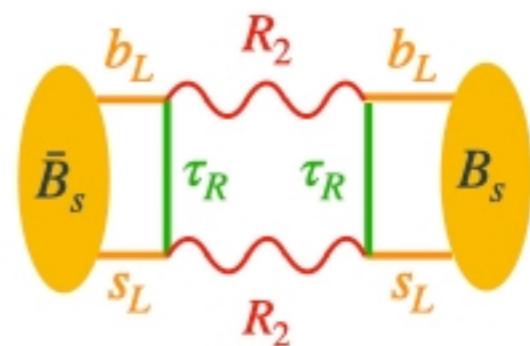
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| U_1 | S_1 | R_2 |
|-------------------------------|--------------------------------|------------------------|
| $C_{lq}^{(3)} = C_{lq}^{(1)}$ | $C_{lq}^{(3)} = -C_{lq}^{(1)}$ | Only $[C_{qe}]_{3333}$ |

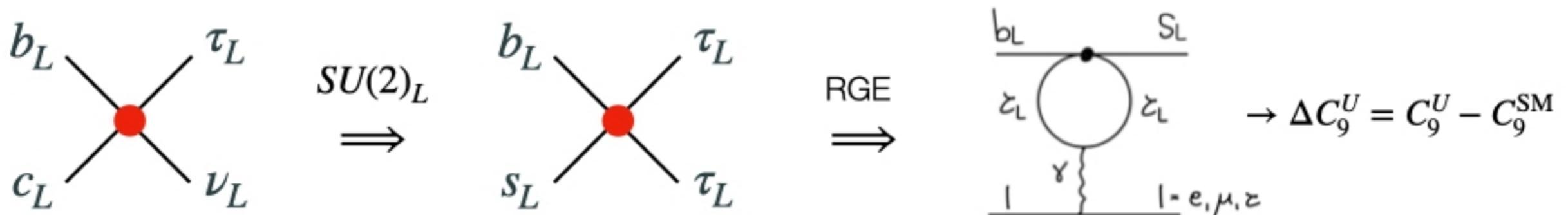


*With both $[C_{qe}]_{3333}$ & $[C_{qe}]_{2333}$ active

[Bobeth, Haisch, [1109.1826](#); Crivellin et al., [1807.02068](#); Algueró et al., [1809.08447](#)] 25

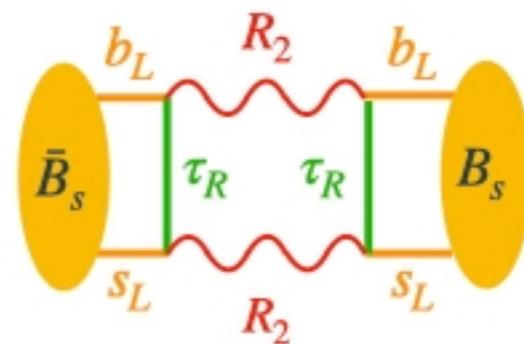
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| U_1 ✓ | S_1 ✗ | R_2 ✗ |
|-------------------------------|--------------------------------|------------------------|
| $C_{lq}^{(3)} = C_{lq}^{(1)}$ | $C_{lq}^{(3)} = -C_{lq}^{(1)}$ | Only $[C_{qe}]_{3333}$ |

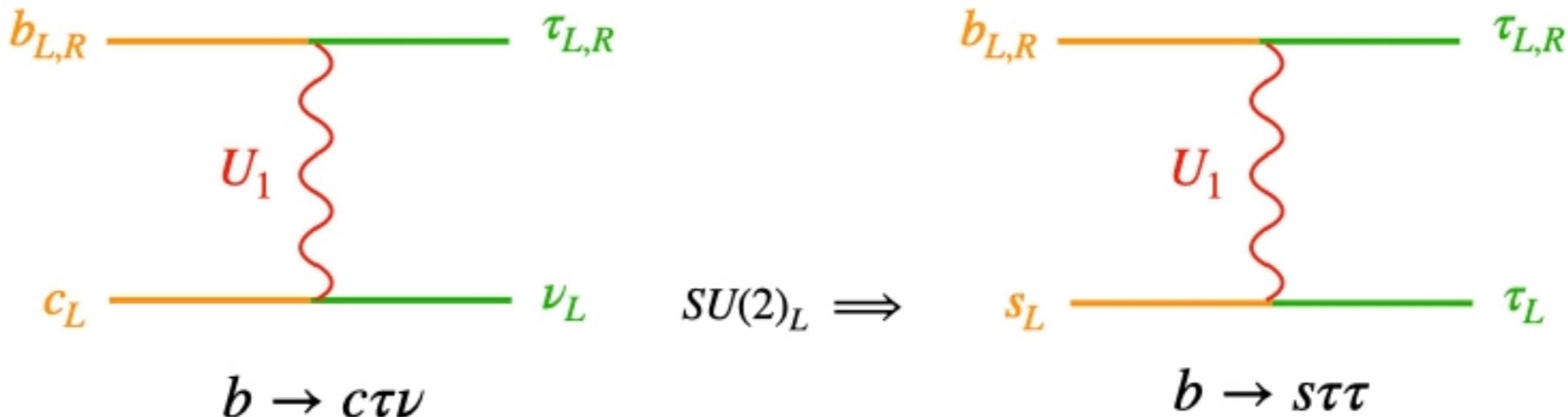


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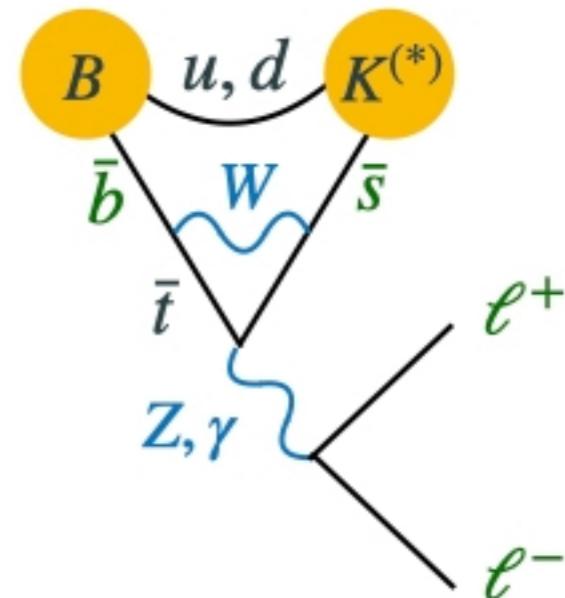
U_1 connects $R_{D^{(*)}}$ to $b \rightarrow s\tau\tau$ observables

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



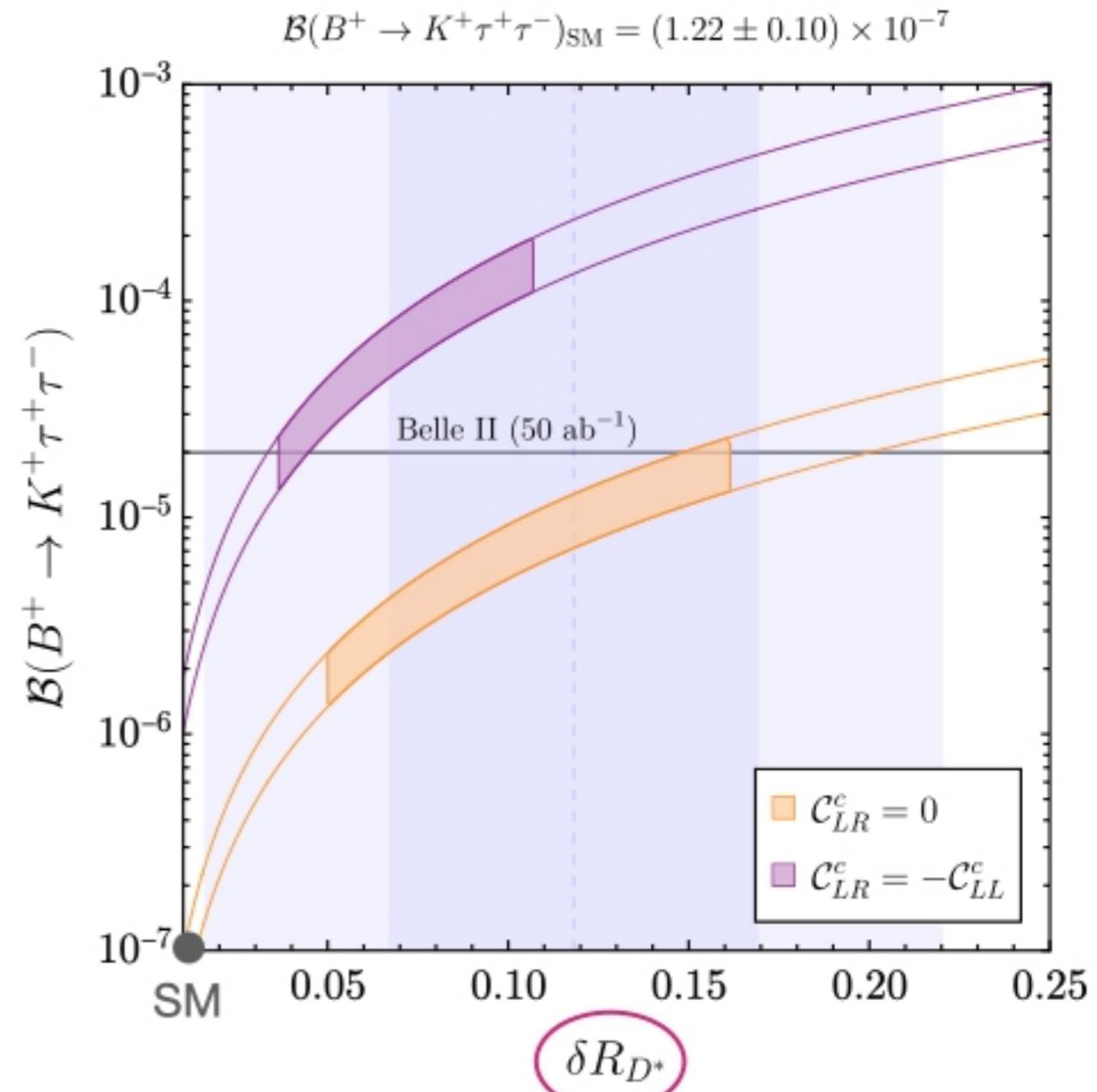
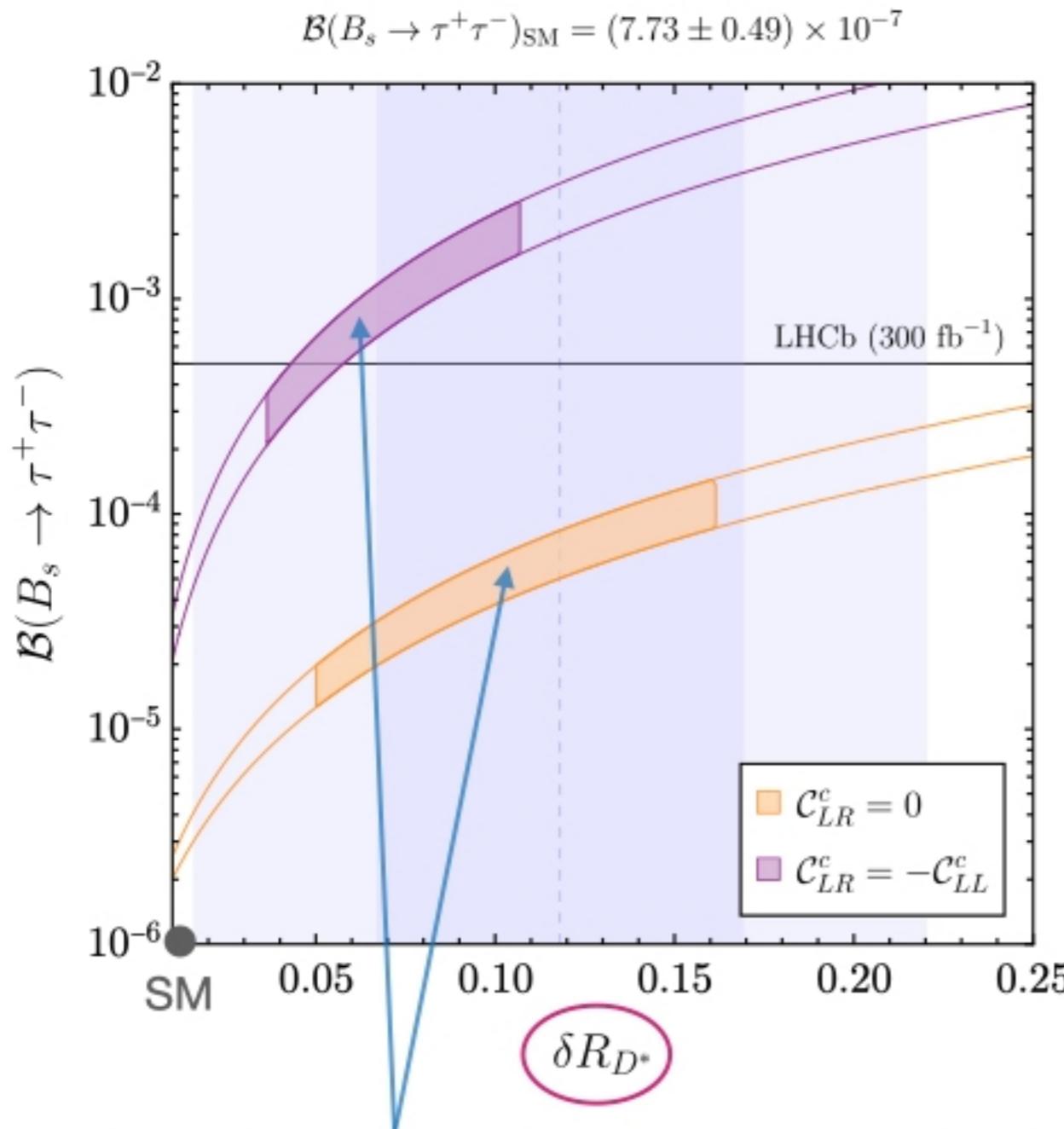
- Since $b \rightarrow s\tau\tau$ is a FCNC, it is a 1-loop process in the SM. We therefore expect a huge NP enhancement in $b \rightarrow s\tau\tau$!

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



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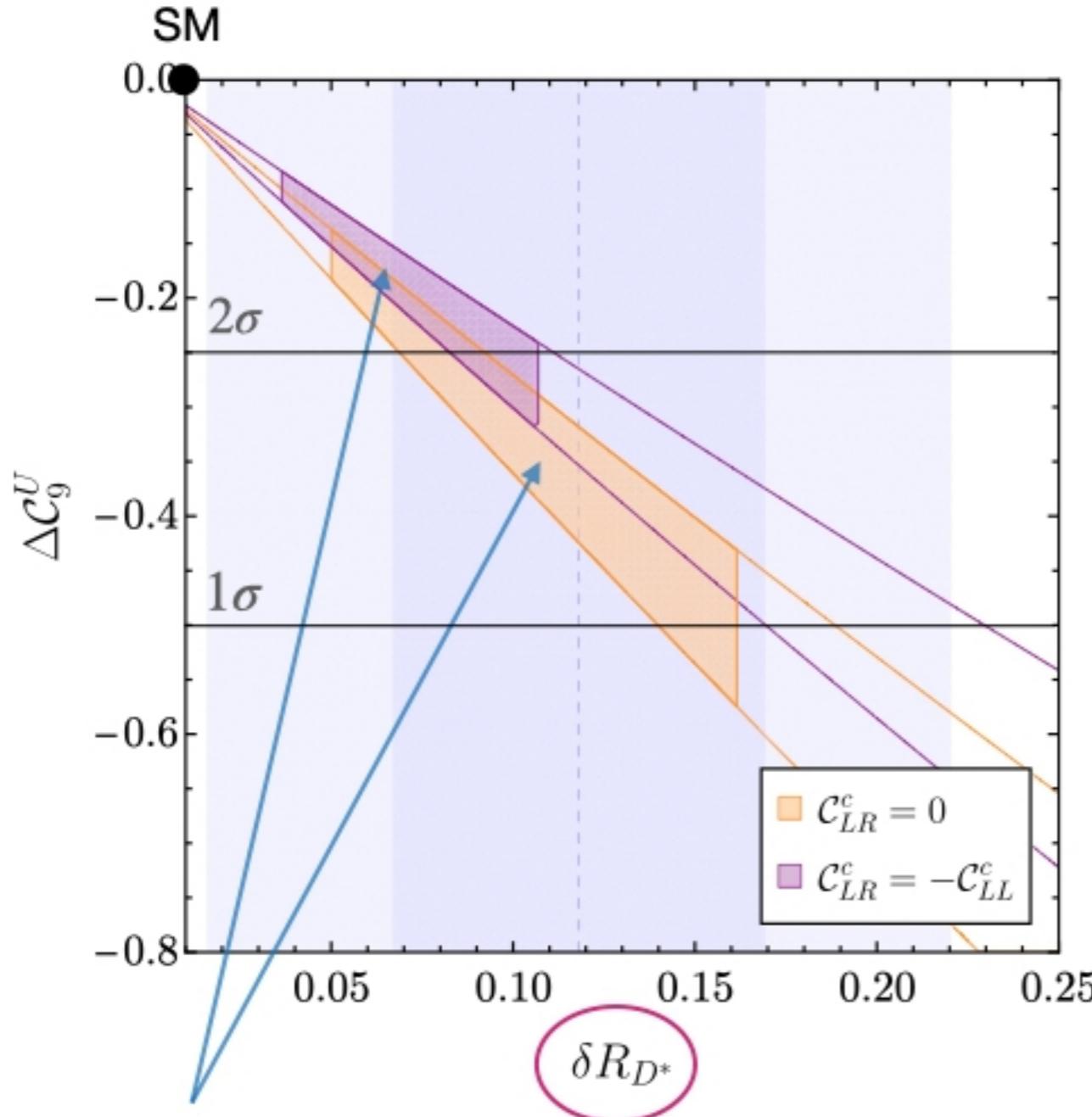


Updated 90% CL region preferred by low-energy $b \rightarrow c\tau\nu$ data [2210.13422](#)

[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 $b \rightarrow s\ell\ell$!



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](#)]

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

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

RGE \implies

$$\rightarrow \Delta C_9^U = C_9^U - C_9^{\text{SM}}$$

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

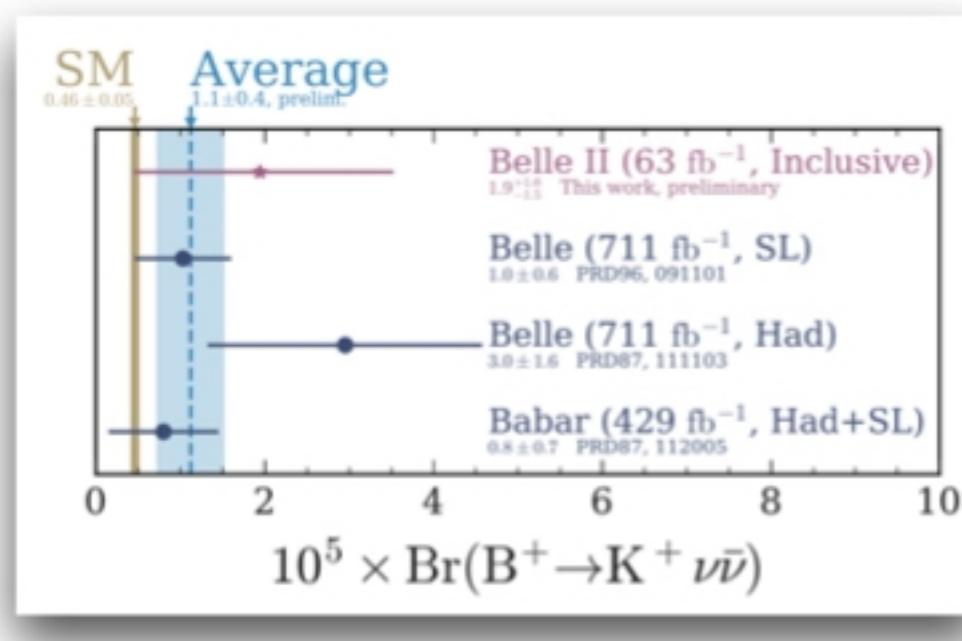
[Altmannshofer, Stangl [2103.13370](#)

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

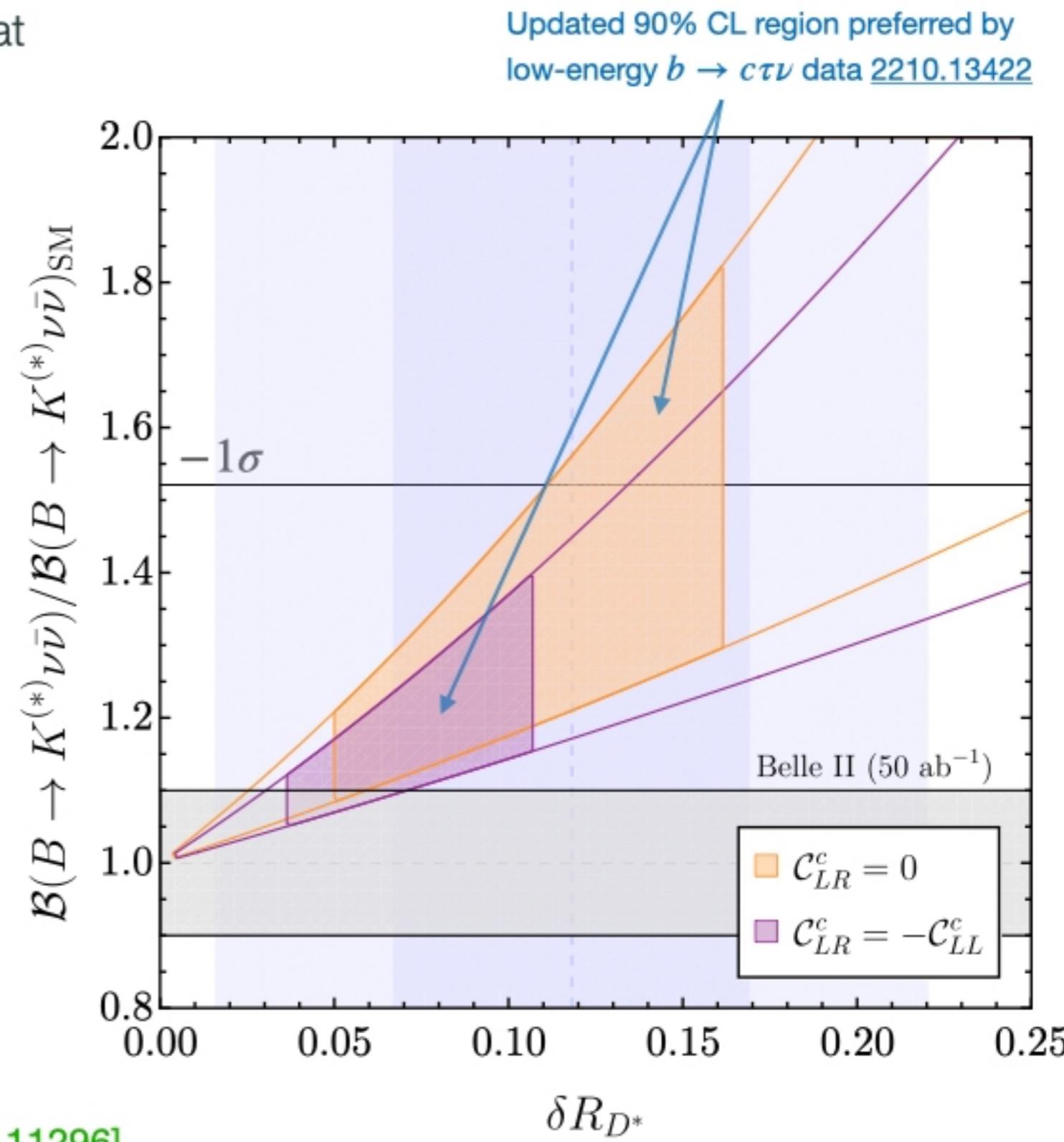
Algueró et al., [1809.08447](#)] 28

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!



[Belle II Collaboration, [2104.12624](#)]



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

Wrapping Up

Overview of ongoing LFU measurements

| mode | Run 1: 3 fb ⁻¹ at 7/8 TeV | | Run 2: 6 fb ⁻¹ 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!

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

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

$$+ C_{S_L} (\bar{c}_R b_L) (\bar{\tau}_R \nu_L) + C_{S_R} (\bar{c}_L b_R) (\bar{\tau}_R \nu_L) + C_T (\bar{c}_R \sigma_{\mu\nu} b_L) (\bar{\tau}_R \sigma^{\mu\nu} \nu_L) \left. \left. \right] + \text{h.c.} \right]$$

SMEFT-LEFT Matching:

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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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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](#)]

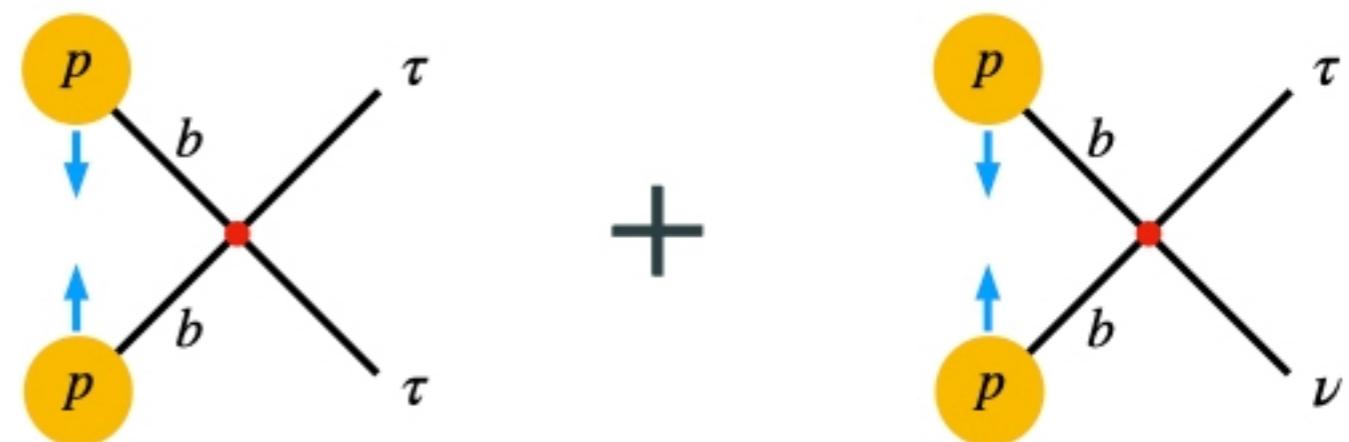
- τ -decays and EW precision observables (EWPO) [LL running in y_t, g_L, g_Y]

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](#)]

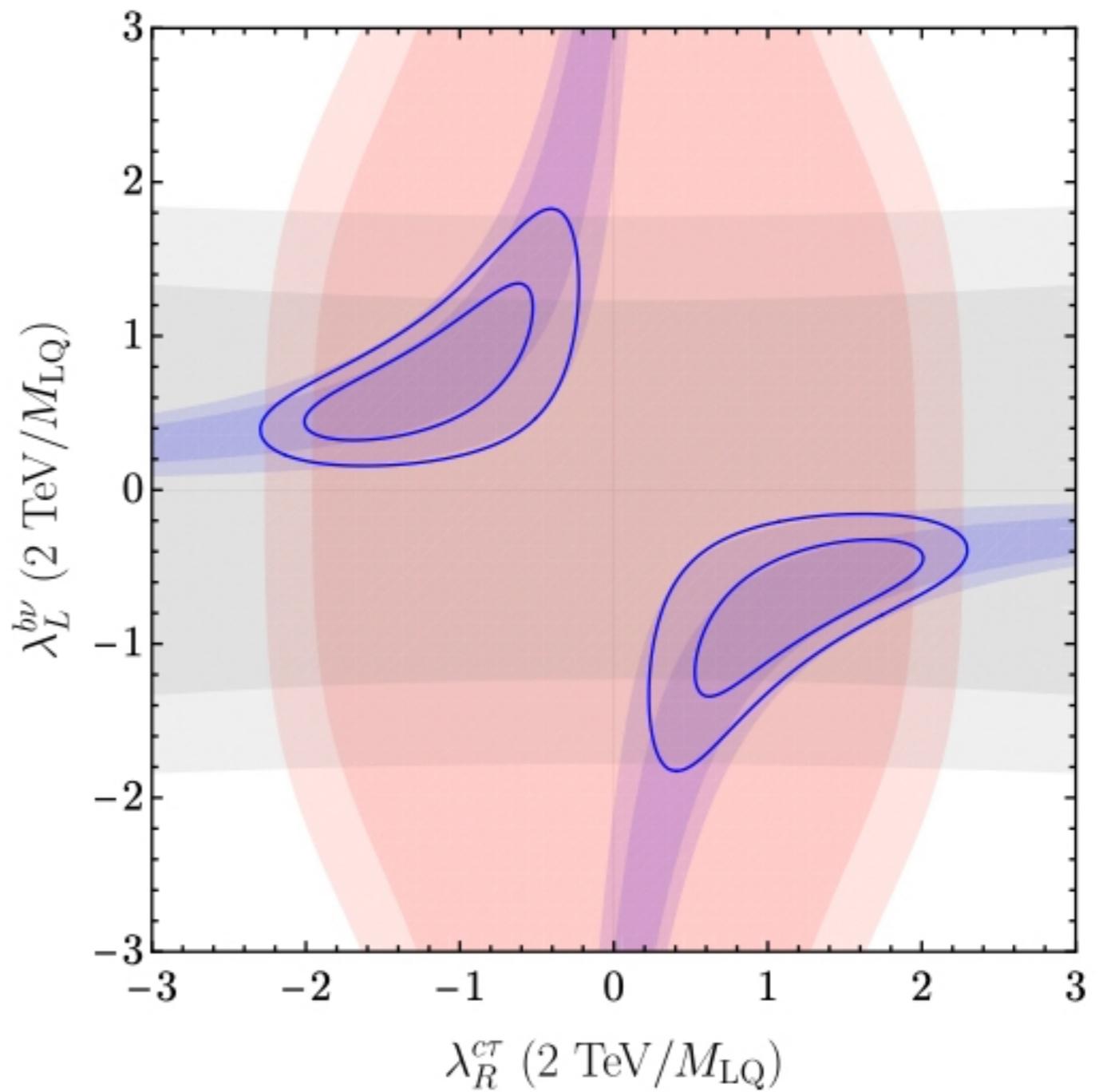
- Data from high- p_T searches at the collider: di-tau $\tau\tau$ and mono-tau $\tau + E_T$


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



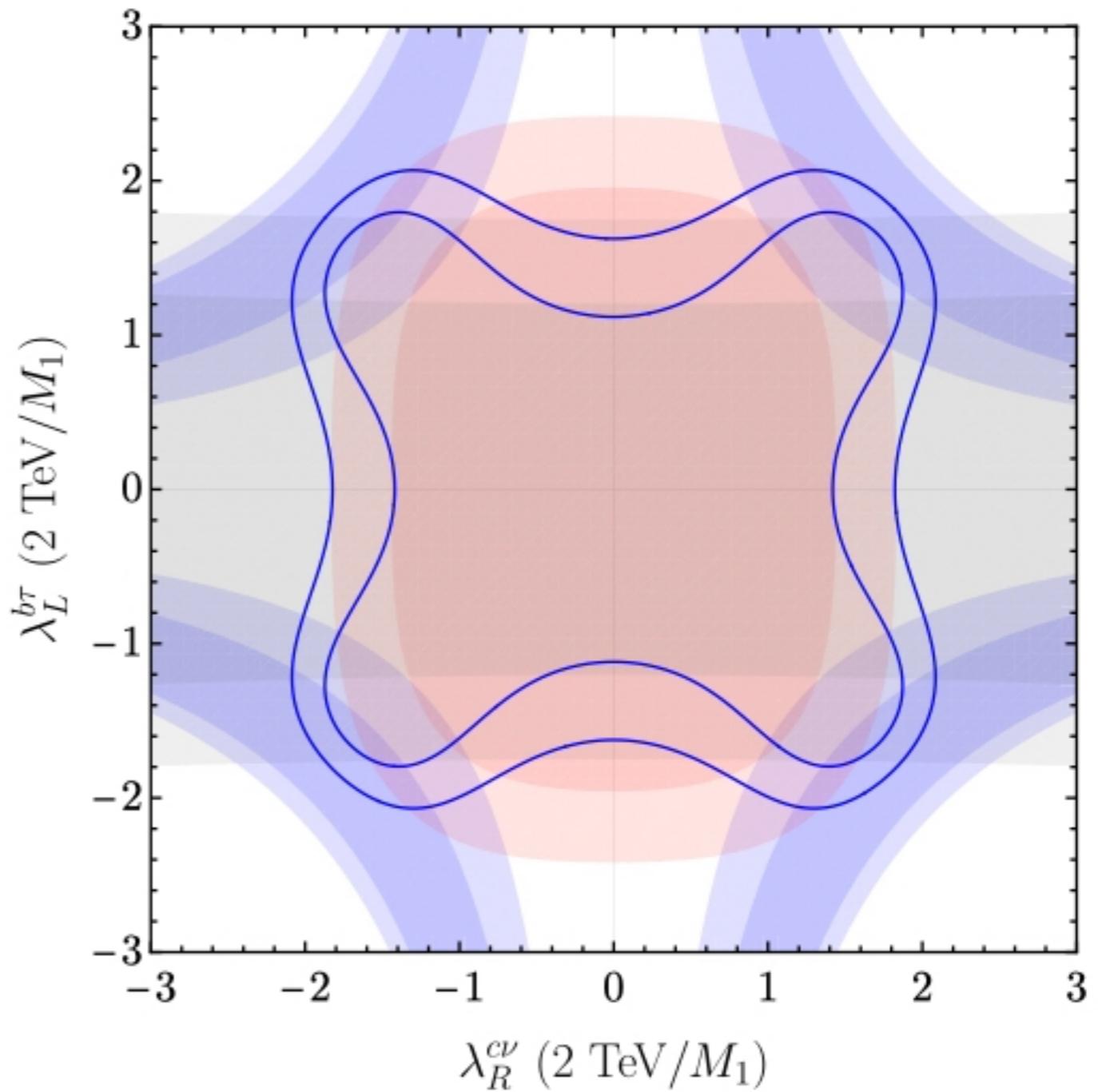
Simplified S_1 scalar LQ model and fit

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



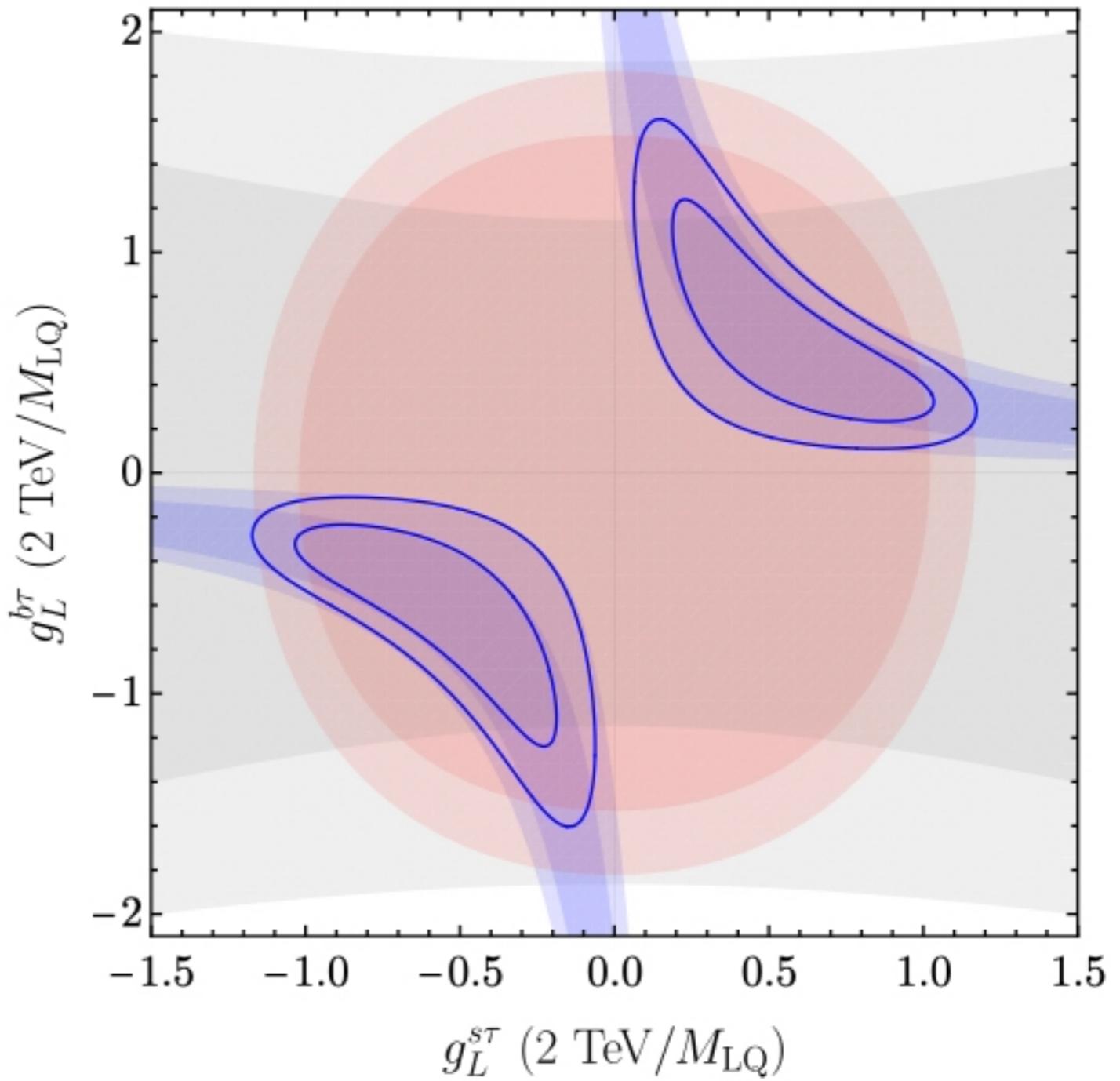
Simplified R_2 scalar LQ model and fit

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

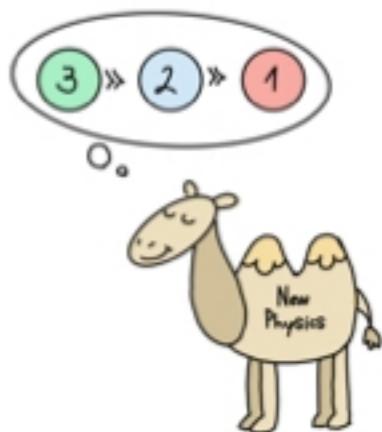


Simplified U_1 vector LQ model and fit

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

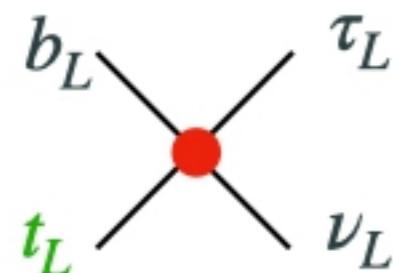


U(2)-like new physics in $b \rightarrow c\tau\nu$ decays



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

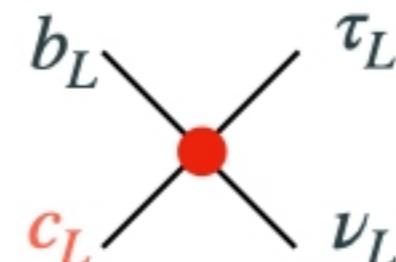
Flavor conserving



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

+

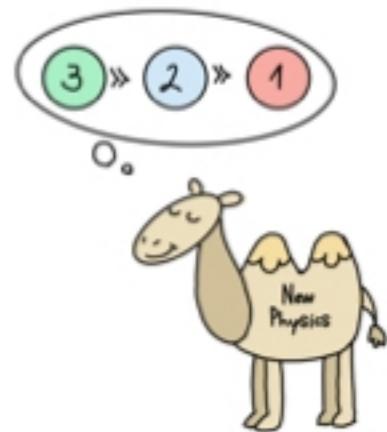
Flavor violating



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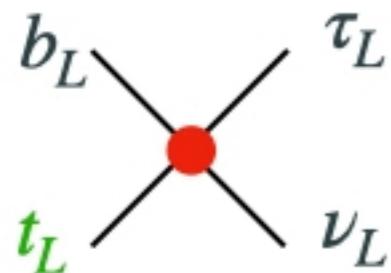
$$\mathcal{A}_{\text{NP}}(b \rightarrow c\tau\nu) = V_{cb}\mathcal{A}_{\text{NP}}^{33} + V_{cs}\mathcal{A}_{\text{NP}}^{23}$$

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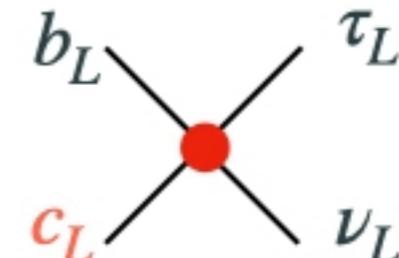
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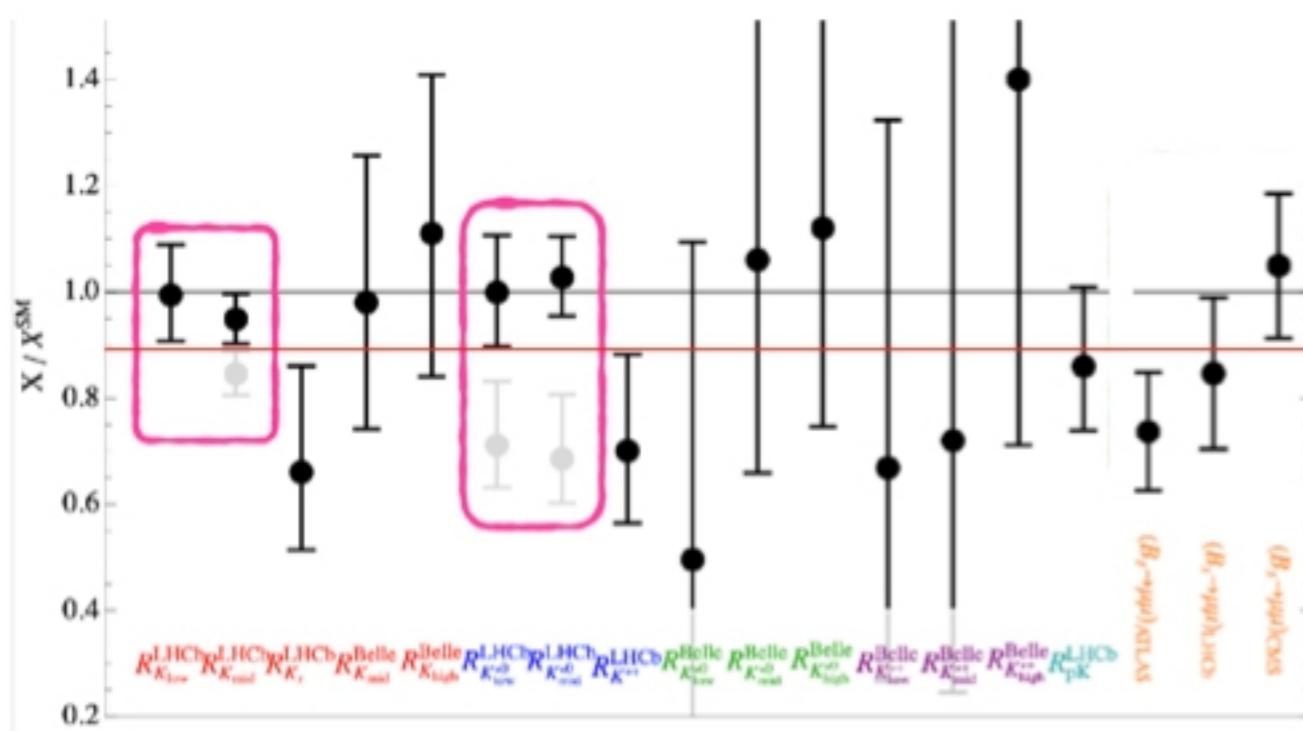
- U(2) suppressed flavor violation means we need an even lower NP scale!

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

$(V_q = 0.1)$

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

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



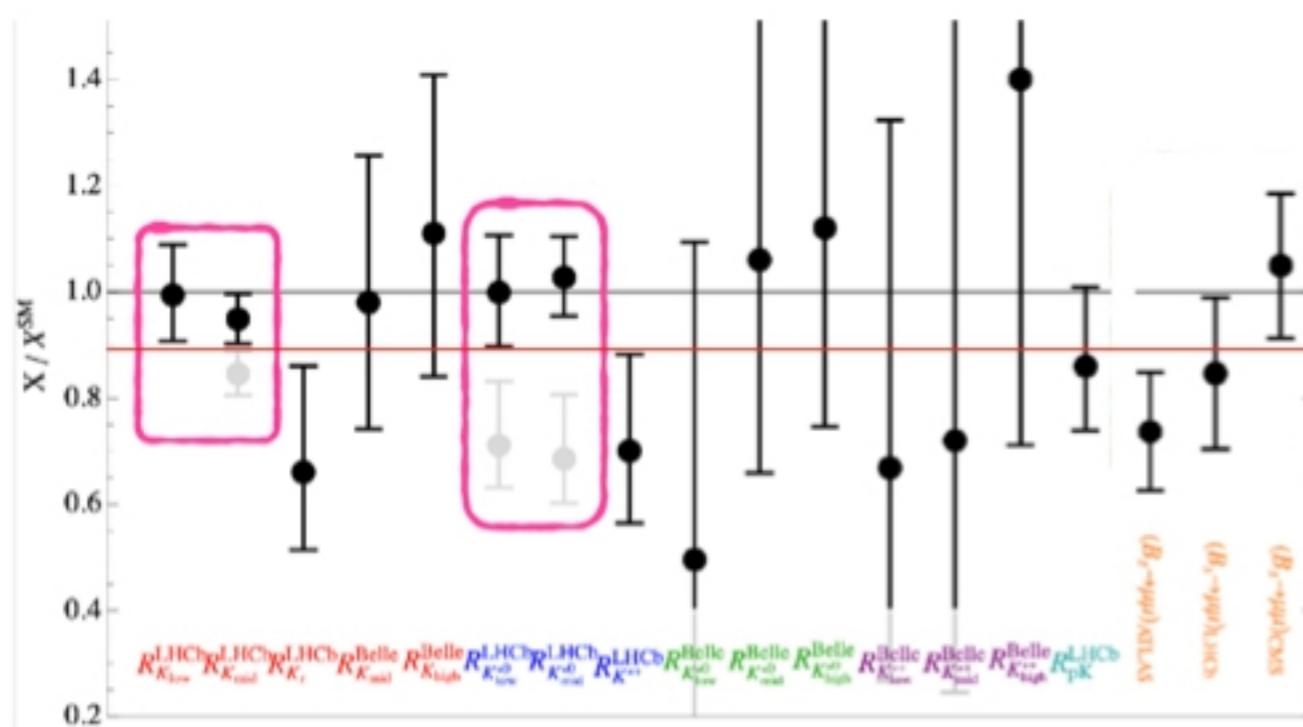
[compilation of $b \rightarrow s\mu\mu$ clean observables as of Dec. 2022 (©David Marzocca)]

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

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

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U(2)-breaking parameter:

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

Nothing changes here,
still calls for light NP!

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

$U(2)_e$ breaking V_e is
simply smaller now.

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

