The Flavor Puzzle: Hints for 3rd Family New Physics

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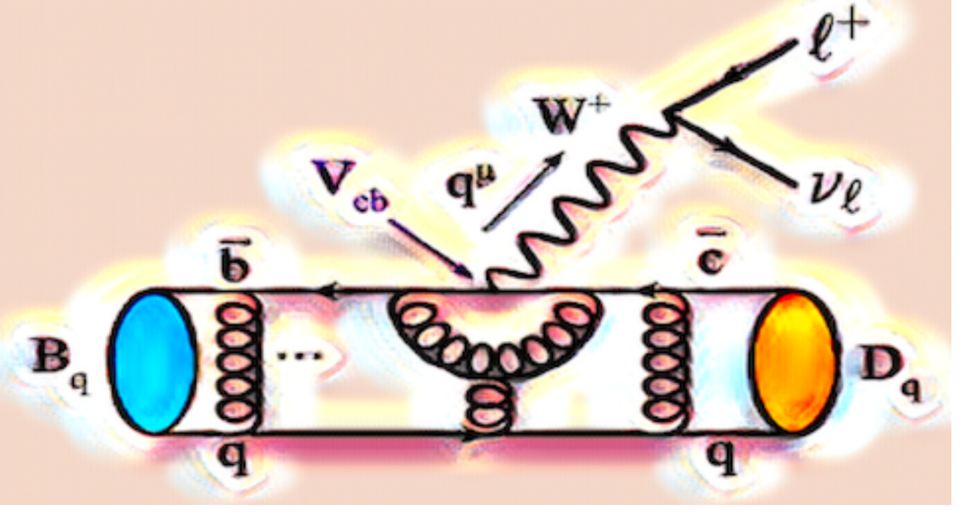
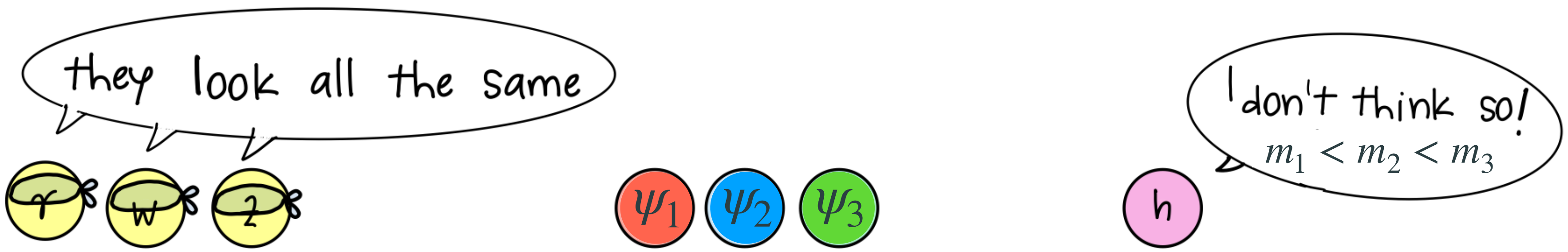


IJS-FMF High-energy Physics Seminar
Jožef Stefan Institute, University of Ljubljana
May the 4th be with you, 2023

It ended, but also begins with the Higgs

- Standard Model (SM) gauge sector is *flavor blind!*

$$\mathcal{G}_F(\text{gauge}) = U(3)^5 \equiv U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$$



- The Higgs, the last piece of the SM discovered in 2012, strongly disagrees! Yukawas with Higgs are the only source of flavor violation in the SM, with a very hierarchical pattern that does not look accidental- *SM flavor puzzle*.

[Credit for cool drawings: Claudia Cornella]

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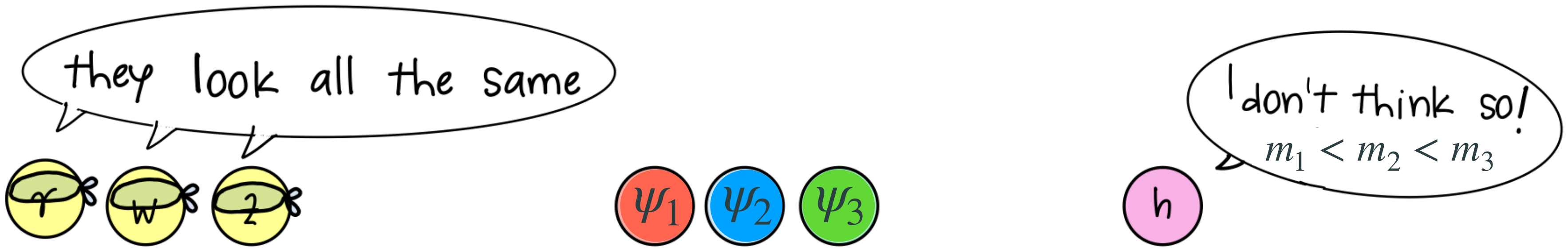

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Flavor Puzzle

Is there a connection between the nature of the Higgs boson and the SM flavor puzzle? Clues toward the structure and scale of new physics (NP)?

[Credit for cool drawings: Claudia Cornella]

Hints of NP structure: Flavor symmetries of the SM

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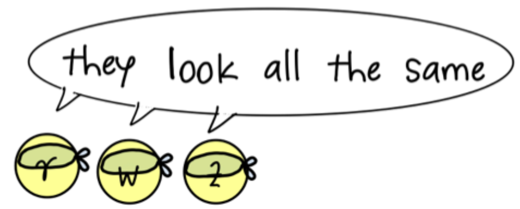
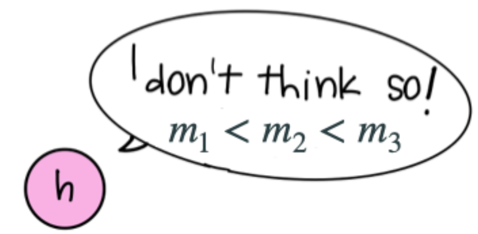


Turn on Yukawas

$$Y_{ij} \bar{\Psi}^i_L H \Psi^j_R$$



$$\mathcal{G}_F(\text{SM}) = U(1)_B \times U(1)_L$$

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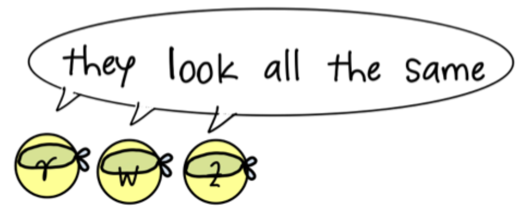

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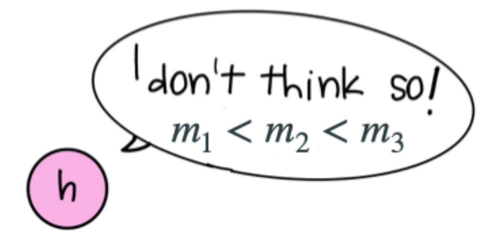

$$\mathcal{G}_F(\text{SM}) = U(1)_B \times U(1)_L$$

- But, since the light family Yukawa couplings are very small:

$$\mathcal{G}_F(\text{SM}) \approx U(2)^5 \equiv U(2)_q \times U(2)_u \times U(2)_d \times U(2)_\ell \times U(2)_e$$

$U(2)^5$ is a good accidental approximate symmetry of the SM!

Hints of NP structure: Flavor symmetries of the SM

- Standard Model (SM) gauge sector is *flavor blind!*

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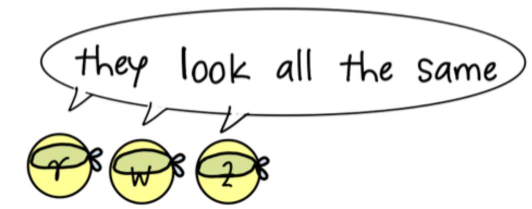

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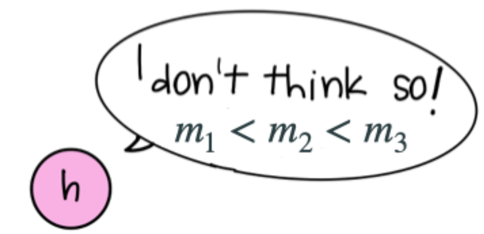

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Flavor Puzzle

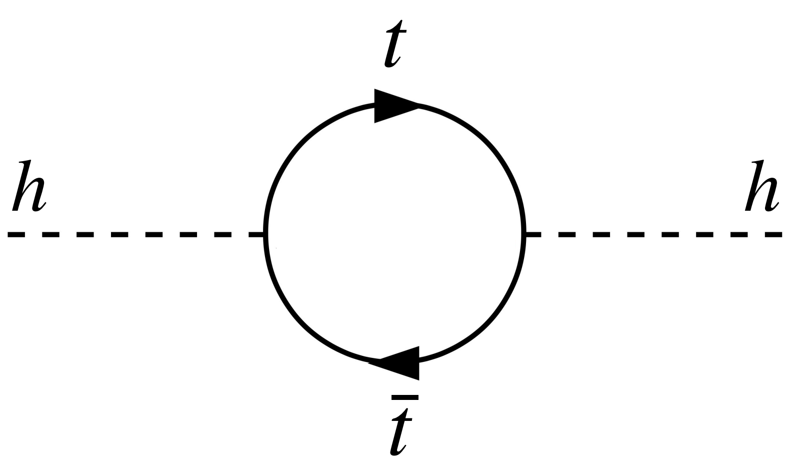
Perhaps this is not an accident- maybe there is NP responsible for this pattern that follows the same structure....

Hints towards NP scale: Nature of the Higgs boson

$\Lambda_{\rm NP}^2$ Higgs Hierarchy Problem

Pre-LHC viewpoint: Nature must be natural!

- The Higgs mass is unstable under quantum corrections- it is quadratically sensitive to NP in the UV. The top Yukawa gives the largest correction:

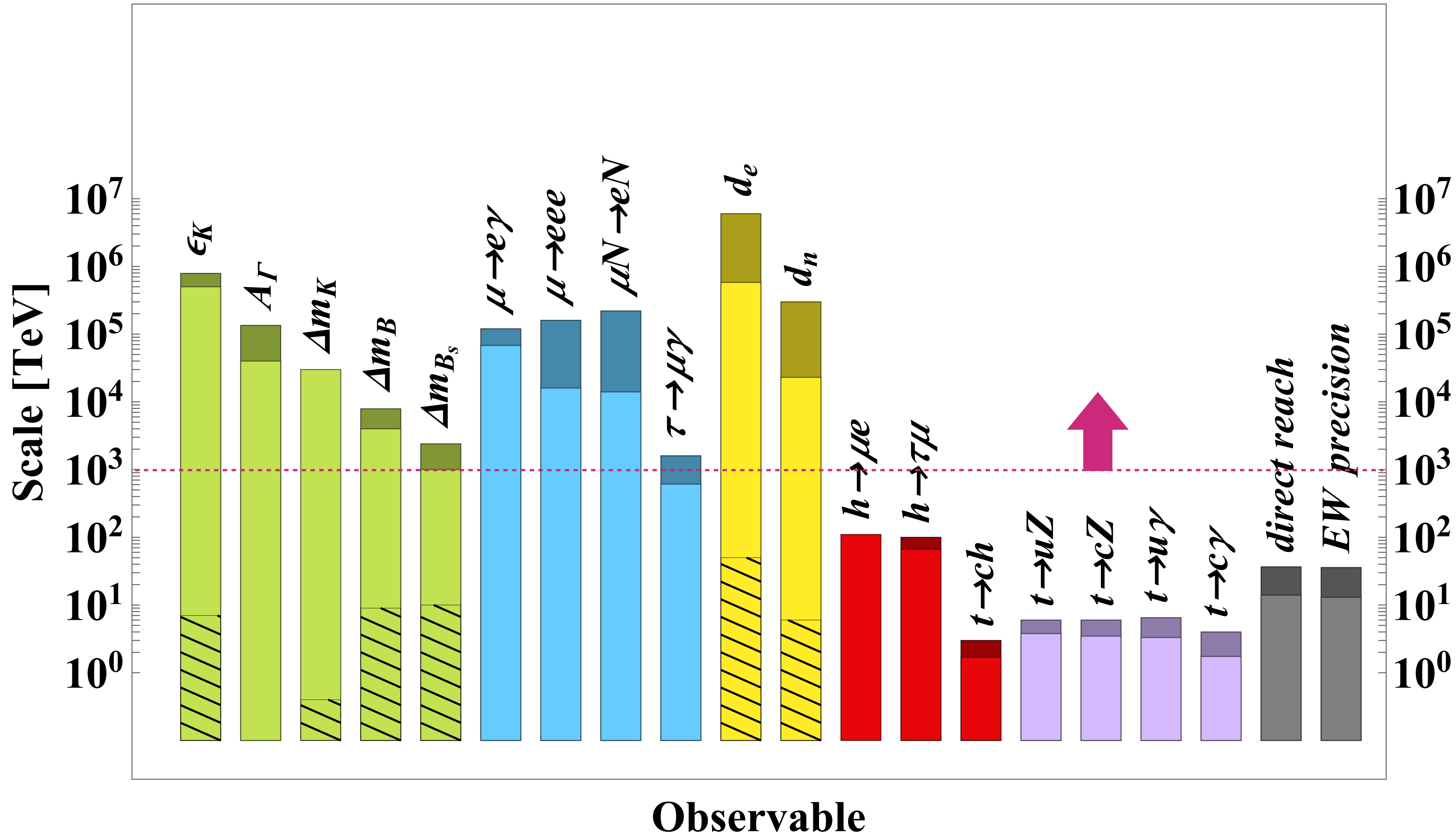


$$\Longrightarrow \qquad \delta m_h^2(\text{top loop}) \approx \frac{3y_t^2}{4\pi^2}\Lambda_{\rm NP}^2$$

- Naturalness principle: Light NP that protects the Higgs mass from large quantum corrections should appear no higher than the TeV scale.

$$\delta m_h^2 / m_h^2 \lesssim 1 \qquad \Longrightarrow \qquad \Lambda_{\rm NP} \lesssim 500 \text{ GeV}$$

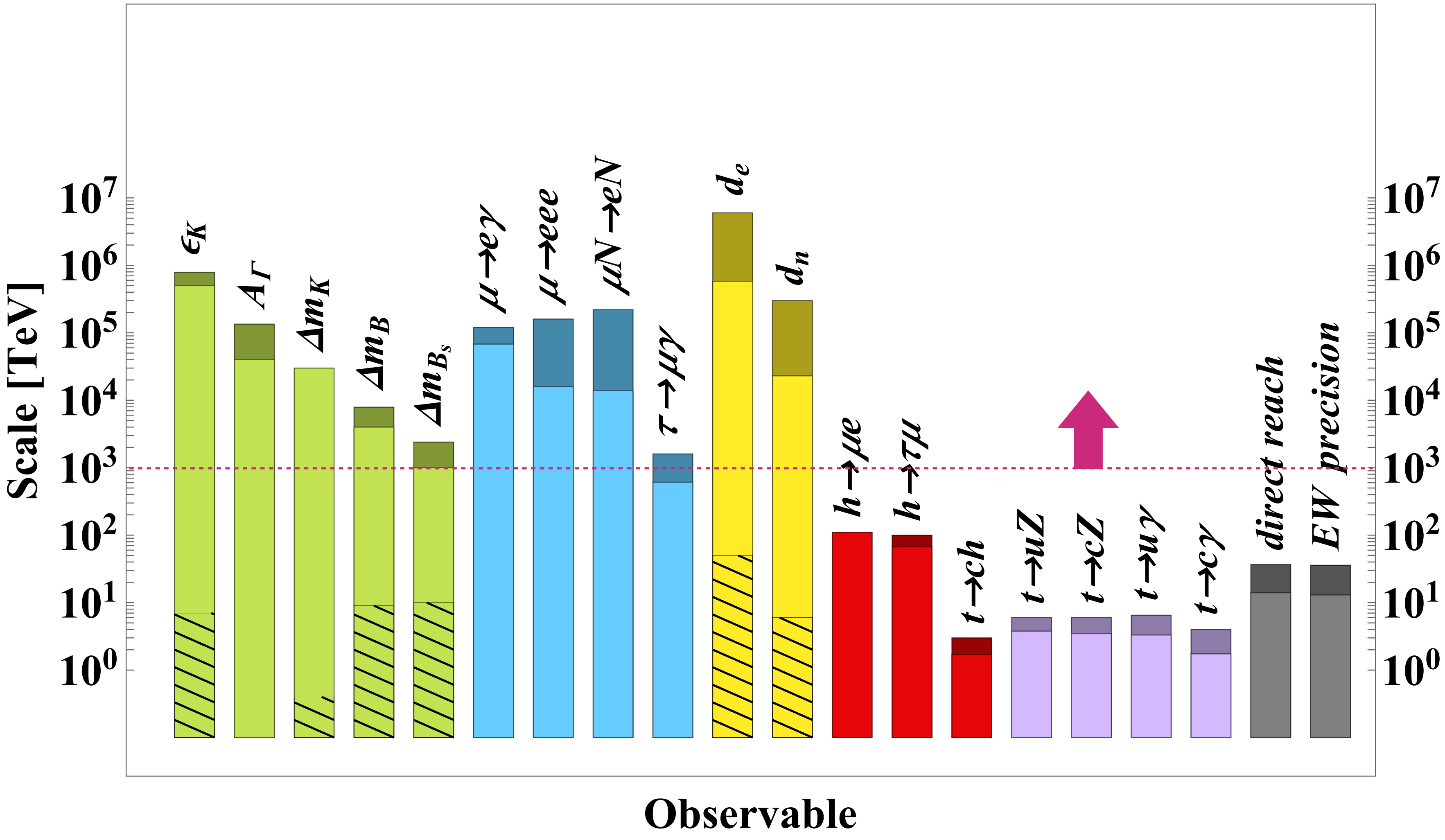
The Flavor Problem of Light New Physics



- Flavor bounds push the scale of flavor anarchic new physics (NP) above 1000 TeV.
- But, to address the EW hierarchy problem, NP must be light. It follows that light NP must have a very specific flavor structure in order to pass flavor bounds.

[Physics Briefing Book 2020, 1910.11775]

The Flavor Problem of Light New Physics



- It follows that light NP must have a very specific flavor structure in order to pass flavor bounds. *SM Yukawa-like flavor protection?*

Λ^2_{NP} **Higgs Hierarchy Problem** ⟷ **Flavor Puzzle**

Minimal Flavor Violation (MFV)

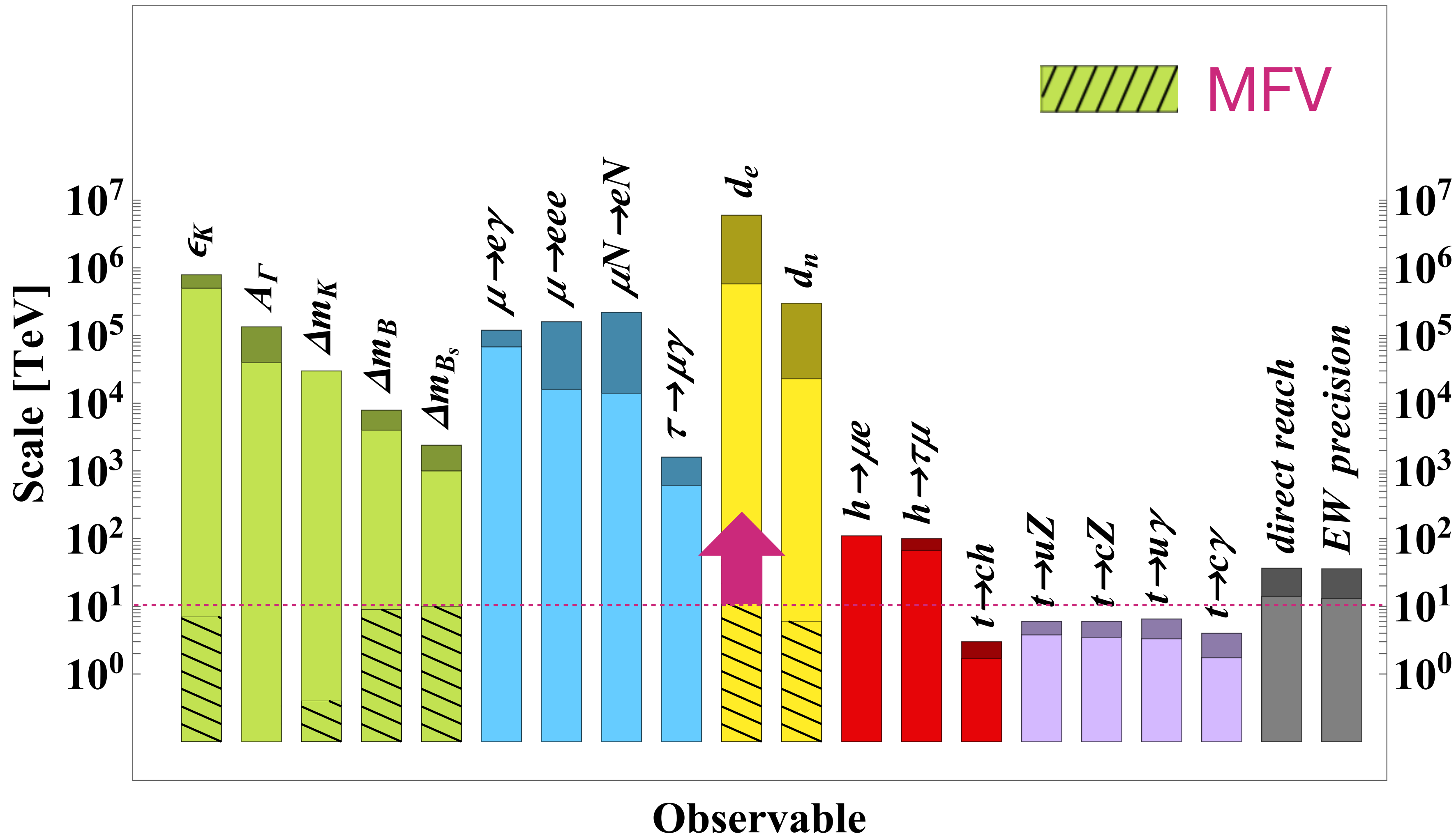
- Key idea: Flavor puzzle probably solved at a high scale. Lightest NP can then be nearly flavor universal. All CP and flavor violation in the NP sector originates from the SM Yukawa couplings.

$$\lambda_{\rm FC} \approx (Y_U Y_U^\dagger)_{\rm FC} \approx y_t^2 \begin{pmatrix} 0 & V_{td}^* V_{ts} & V_{td}^* V_{tb} \\ V_{td} V_{ts}^* & 0 & V_{ts}^* V_{tb} \\ V_{td} V_{tb}^* & V_{ts} V_{tb}^* & 0 \end{pmatrix} \sim \begin{pmatrix} 0 & \lambda^5 & \lambda^3 \\ \lambda^5 & 0 & \lambda^2 \\ \lambda^3 & \lambda^2 & 0 \end{pmatrix}$$

Minimally flavour violating dimension six operator	main observables	Λ [TeV] −	+	
$\mathcal{O}_0 = \frac{1}{2}(\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)^2$	ϵ_K, Δm_{B_d}	6.4	5.0	
$\mathcal{O}_{F1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} Q_L\right) F_{\mu\nu}$	$B \to X_s \gamma$	9.3	12.4	
$\mathcal{O}_{G1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} T^a Q_L\right) G^a_{\mu\nu}$	$B \to X_s \gamma$	2.6	3.5	
$\mathcal{O}_{\ell 1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$	$B \to (X)\ell\bar{\ell}$, $K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.1	2.7	*
$\mathcal{O}_{\ell 2} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu \tau^a Q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	$B \to (X)\ell\bar{\ell}$, $K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.4	3.0	*
$\mathcal{O}_{H1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	$B \to (X)\ell\bar{\ell}$, $K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	1.6	1.6	*
$\mathcal{O}_{q5} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{D}_R \gamma_\mu D_R)$	$B \to K\pi$, $\epsilon'/\epsilon, \ldots$	~ 1		

[G. D'Ambrosio, G.F. Giudice, G. Isidori, A. Strumia, hep-ph/0207036]

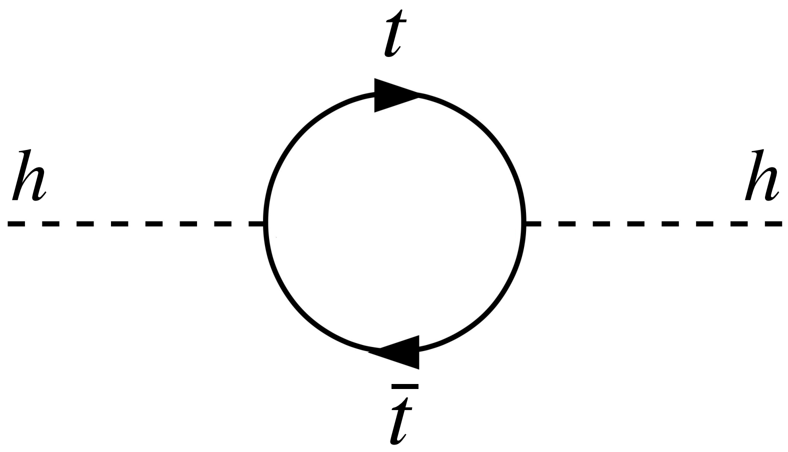
Minimal Flavor Violation 20 Years Later



- In the case of flavor universal NP + MFV, NP couples to valence quarks!
- For this reason, flavor bounds are still ok, but ***direct searches*** at the LHC push MFV new physics to the 10 TeV ballpark.

Naturalness Paradigm 20 Years Later

Higgs Hierarchy Problem



$$\Longrightarrow \qquad \delta m_h^2(\text{top loop}) \approx \frac{3y_t^2}{4\pi^2}\Lambda_{\text{NP}}^2$$

- Light NP protecting the Higgs mass from large corrections should appear. That didn't happen so far. If NP is almost flavor universal, we now have an experimentally proven "little hierarchy problem":

$$\Lambda_{\text{NP}} \gtrsim 10 \text{ TeV} \qquad \Longrightarrow \qquad m_h^2/\delta m_h^2 \sim 10^{-3}$$

So, did naturalness fail as a paradigm?

- This seems to be an increasingly common viewpoint. Personal opinion: Indeed, we were too aggressive, but this view is overly pessimistic.

$$m_h^2/\delta m_h^2 \sim 10^{-3} \qquad \text{vs.} \qquad m_h^2/M_P^2 \sim 10^{-34}$$

$(\Lambda_{\text{NP}} \sim 10$ TeV$)$ $\qquad$ $(\Lambda_{\text{NP}} \sim M_P)$

- Nature seems a bit fine-tuned. However, I would not discard naturalness arguments: they still provide the best hope that light NP could be around the corner.
- Can we do better than 10 TeV? To answer this question, we need to ask: Is there a "more natural" flavor protection for NP?

U(2) is the natural successor to MFV

- Key idea: New physics is **NOT** flavor universal. In particular, there are new flavor non-universal interactions at the TeV scale coupled dominantly to the third family. NP coupled to Higgs & top is what we need to address the hierarchy problem.
- Unlike in the MFV case, these new interactions see flavor just like the SM Higgs. They could be connected to a low scale solution to the SM flavor puzzle.

[R. Barbieri, G. Isidori, J. Jones-Perez, P. Lodone, D. Straub, 1105.2296] [See also: Davighi, Isidori, 2303.01520]

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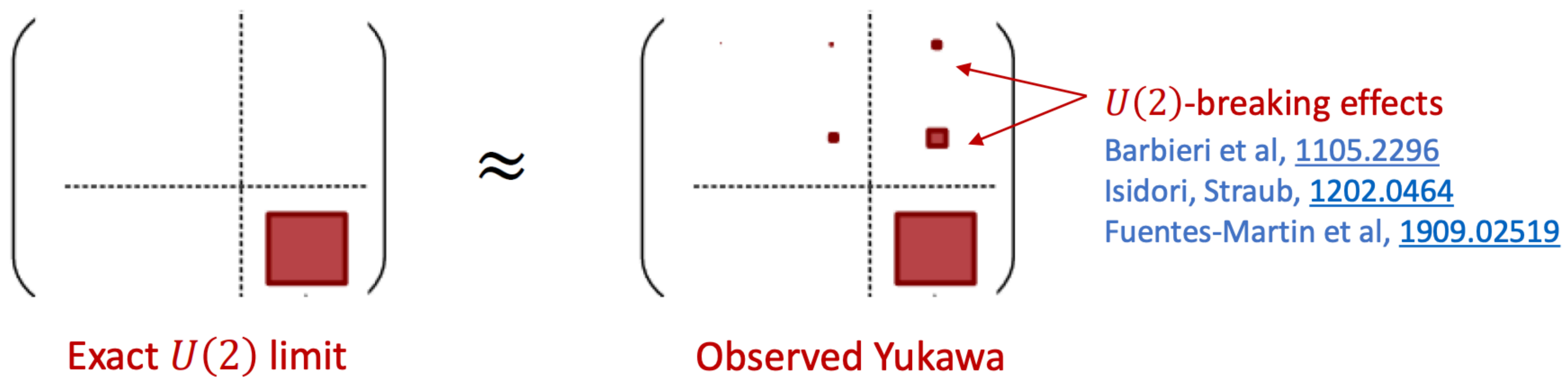
- Unlike in the MFV case, these new interactions see flavor just like the SM Higgs. They could be connected to a low scale solution to the SM flavor puzzle.
- NP dominantly coupled to the third family quarks (+leptons) enjoys a $U(2)^3$ ($U(2)^5$) flavor symmetry, just like the SM Yukawa couplings.



NP coupled only to 3rd family

Also small couplings to light families

[R. Barbieri, G. Isidori, J. Jones-Perez, P. Lodone, D. Straub, 1105.2296]

[See also: Davighi, Isidori, 2303.01520]

U(2) compared with MFV

Flavor diagonal couplings (direct searches)

- In the exact U(2) limit, we have flavor diagonal, but non-universal NP.

Exact U(3)	Exact U(2)
$\bar{q}_L^a \gamma_\mu q_L^a$	$\bar{q}_L^3 \gamma_\mu q_L^3 + \epsilon\, \bar{q}_L^i \gamma_\mu q_L^i$

- *Key benefit*: Different NP coupling for light families makes it possible to suppress couplings to valence quarks and relax direct search bounds.

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Flavor violating couplings

$$\underline{\text{MFV: Minimally broken U(3)}} \qquad \qquad \underline{\text{Minimally broken U(2)}}$$

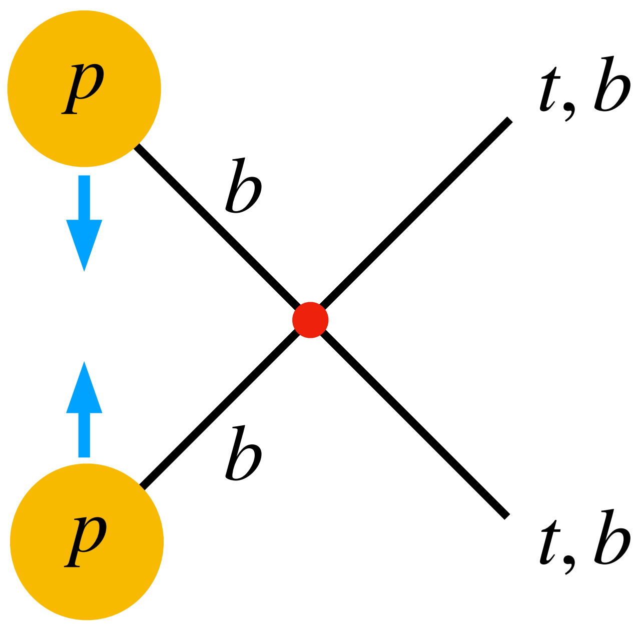
$$\bar{q}_L^a \lambda_{\rm FC}^{ab} \gamma_\mu q_L^b \qquad \qquad \bar{q}_L^i V_q^i \gamma_\mu q_L^3 \qquad \qquad V_q \sim \mathcal{O}\begin{pmatrix} V_{td} \\ V_{ts} \end{pmatrix}$$

Model independent pheno of the U(2) hypothesis

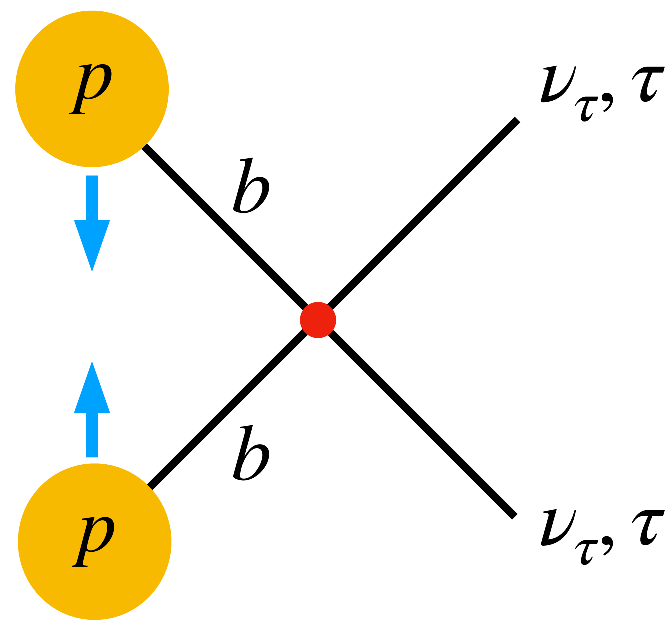
Flavor diagonal couplings: $\bar{q}_L^3\gamma_\mu q_L^3 + \epsilon\,\bar{q}_L^i\gamma_\mu q_L^i + \bar{\ell}_L^3\gamma_\mu \ell_L^3$

- Third family direct searches at the LHC (limit $\epsilon \to 0$)

$U(2)^3$ (quarks only)



$U(2)^5$ (also leptons)



- Signals: $t\bar{t}$, $b\bar{b}$ and $t\bar{b}$

Drell-Yan $\tau\bar{\tau}$ and mono-τ + E_T

Model Independent pheno of the U(2) hypothesis

Flavor violating couplings: $\bar{q}_L^i V_q^i \gamma_\mu q_L^3\,, \qquad V_q^T \sim \mathcal{O}\left(V_{td},\, V_{ts}\right)$

- Leading effects: 3 → 2 transitions: top decays, *B*-physics, tau decays. Focus here on the operators for *B*-physics one can construct together with $\bar{\ell}_L^3 \gamma^\mu \ell_L^3$:

U(2)-breaking operator	Process	Example Observables
$(\bar{q}_L^i V_q^i \gamma_\mu q_L^3)^2$	*B*-meson mixing	$\Delta M_{B_s}\,, \Delta M_{B_d}$
$(\bar{q}_L^i V_q^i \gamma_\mu q_L^3)(\bar{\ell}_L^3 \gamma^\mu \ell_L^3)$	Neutral current *B*-decays	$B \to K^{(*)}\tau\bar{\tau}\,,\ B \to K^{(*)}\nu_\tau\bar{\nu}_\tau\,,\ B_s \to \tau\bar{\tau}$
$(\bar{q}_L^i V_q^i \gamma_\mu \sigma^I q_L^3)(\bar{\ell}_L^3 \gamma^\mu \sigma^I \ell_L^3)$	Charged current *B*-decays	$B \to D^{(*)}\tau\bar{\nu}_\tau\,,\ \Lambda_b \to \Lambda_c\tau\bar{\nu}_\tau\,,\ B_c \to \tau\bar{\nu}_\tau$
$(\bar{q}_L^i V_q^i \gamma^\mu q_L^3)(H^\dagger D_\mu H)$	Neutral current *B*-decays	$B \to K^{(*)}\ell\bar{\ell}\,,\ B \to K^{(*)}\nu_\ell\bar{\nu}_\ell\,,\ B_s \to \ell\bar{\ell}$
$y_b\,(\bar{q}_L^i V_q^i \sigma_{\mu\nu} H b_R) F^{\mu\nu}$	Neutral current *B*-decays	$B \to X_s\gamma$

Model Independent pheno of the U(2) hypothesis

Flavor violating couplings: $\bar{q}^i_L V^i_q \gamma_\mu q^3_L$, $\quad V^T_q \sim \mathcal{O}\left(V_{td}, V_{ts}\right)$

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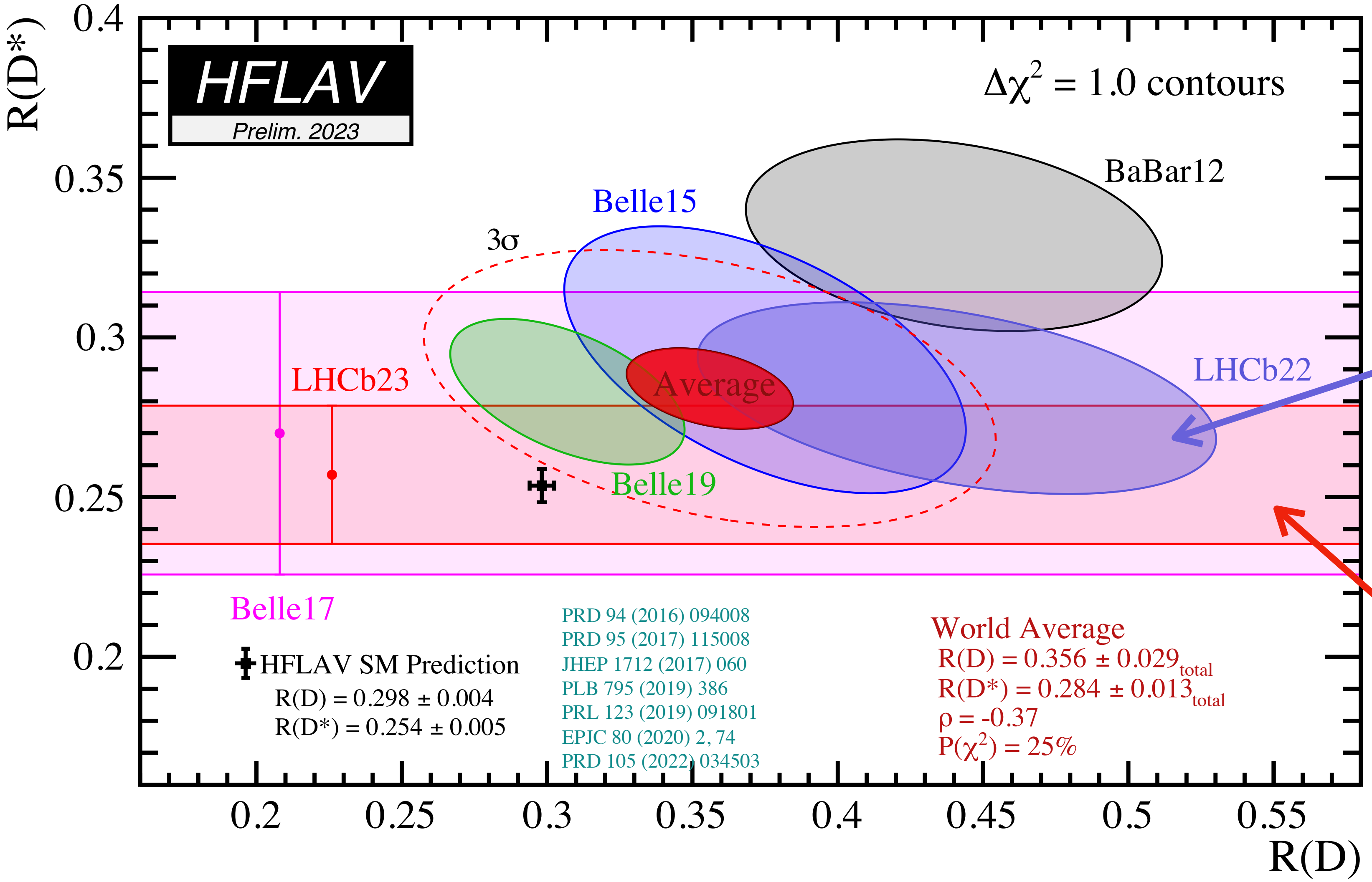
$(\bar{q}^i_L V^i_q \gamma_\mu \sigma^I q^3_L)(\bar{\ell}^3_L \gamma^\mu \sigma^I \ell^3_L)$	Charged current *B*-decays	$B \to D^{(*)}\tau\bar{\nu}_\tau, \; \Lambda_b \to \Lambda_c\tau\bar{\nu}_\tau, \; B_c \to \tau\bar{\nu}_\tau$
$(\bar{q}^i_L V^i_q \gamma^\mu q^3_L)(H^\dagger D_\mu H)$	Neutral current *B*-decays	$B \to K^{(*)}\ell\bar{\ell}, \; B \to K^{(*)}\nu_\ell\bar{\nu}_\ell, \; B_s \to \ell\bar{\ell}$
$y_b\,(\bar{q}^i_L V^i_q \sigma_{\mu\nu} H b_R) F^{\mu\nu}$	Neutral current *B*-decays	$B \to X_s\gamma$

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.

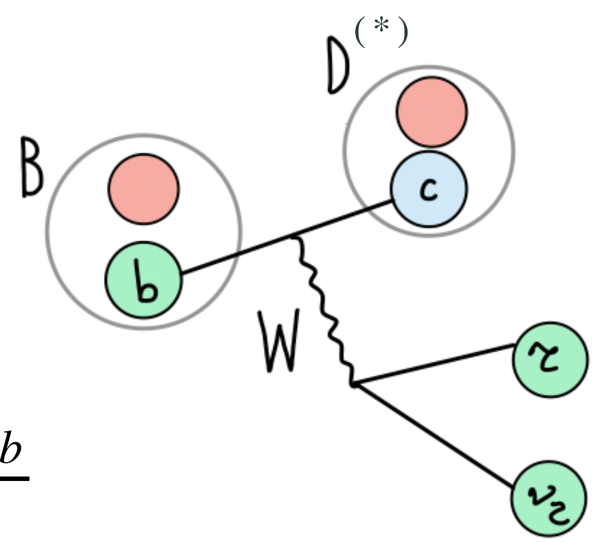
- Theoretically clean. Measurements by Babar, Belle, LHCb in good agreement.
- Enhancement of $\sim 10\,\%$ over SM due to excess in tau mode: $B \to D^{(*)}\tau\bar{\nu}_\tau$. ✔
- Combined, $3.2\,\sigma$ **tension** w.r.t SM. Measurement of $R_{\Lambda_c}/R_{\Lambda_c}^{\text{SM}} = 0.73 \pm 0.23$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

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

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

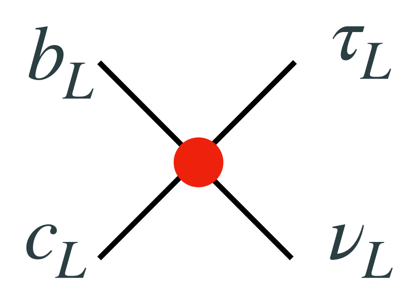
- We need ~10% of a tree-level SM process due to NP. Heavy NP should therefore also be tree-level to compete. Consider Fermi-like LH NP:

SM process



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

Heavy new physics

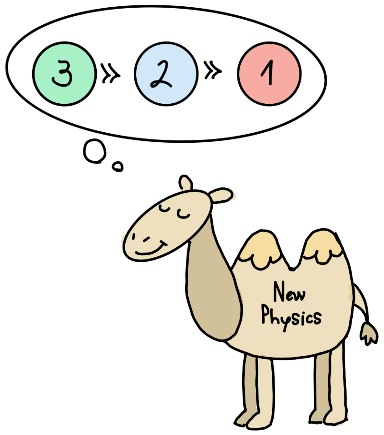


$$\mathscr{A}_{\rm NP} \sim \frac{1}{\Lambda_{\rm NP}^2}$$

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

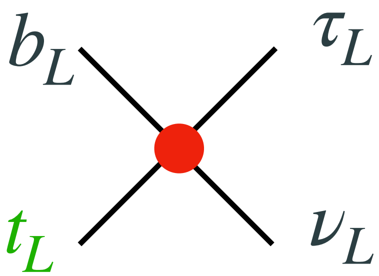
$$2\frac{\mathscr{A}_{\rm NP}}{\mathscr{A}_{\rm SM}} = \frac{v^2}{V_{cb}\Lambda_{\rm NP}^2} \approx \delta R_{D^*} \quad \Longrightarrow \quad \Lambda_{\rm NP} \approx \frac{v}{\sqrt{V_{cb}\,\delta R_{D^*}}} \approx 3.6 \text{ TeV} \left(\frac{0.12}{\delta R_{D^*}}\right)^{1/2}$$

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



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

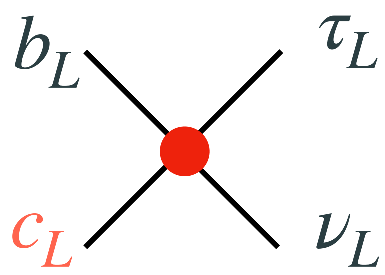
Flavor conserving



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

$+$

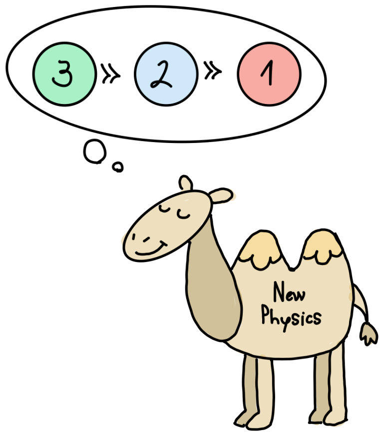
Flavor violating



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

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

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



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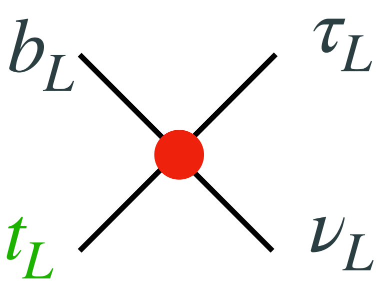

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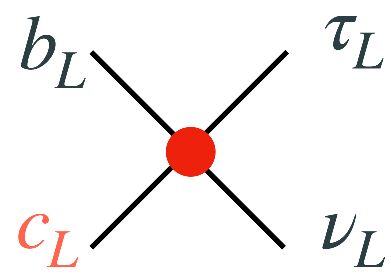
$+$

Flavor violating



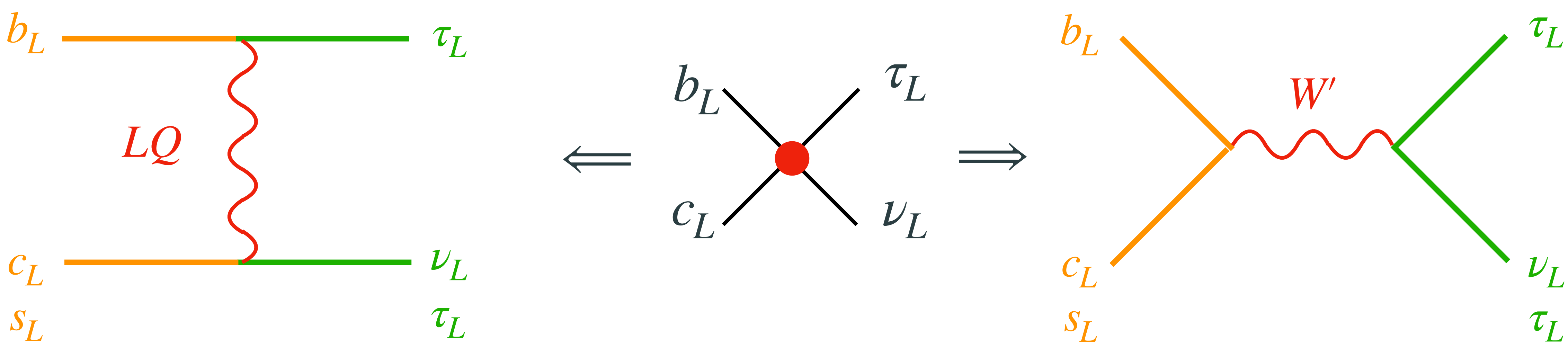
$$\mathscr{A}_{\rm NP}^{23} \sim \frac{V_q}{\Lambda_{\rm NP}^2}$$

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

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

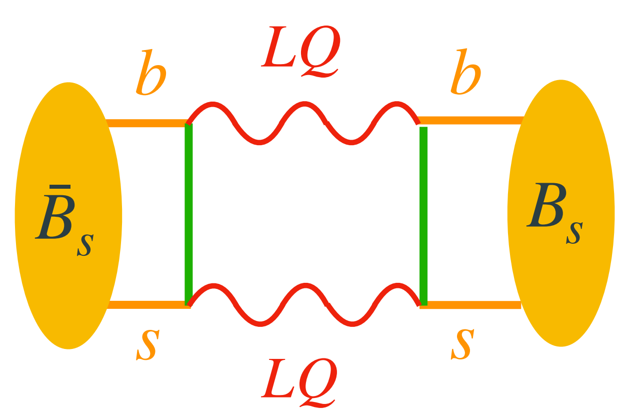
$$2\frac{\mathscr{A}_{\rm NP}}{\mathscr{A}_{\rm SM}} \approx \frac{v^2}{\Lambda_{\rm NP}^2}\left(1 + \frac{V_q}{V_{cb}}\right) \approx \delta R_{D^*} \quad \underset{(V_q = 0.1)}{\Longrightarrow} \quad \Lambda_{\rm NP} \approx 1.3 \text{ TeV} \left(\frac{0.12}{\delta R_{D^*}}\right)^{1/2}$$

What kind of new particles could we have?

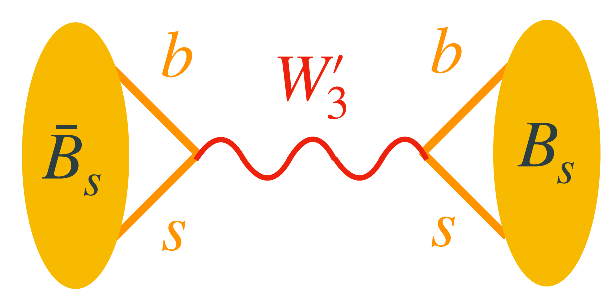


- LH NP $\Longrightarrow$ $b \to s\tau\tau(\nu\nu)$ couplings. LQ's have two important advantages

1. $\Delta F = 2$:

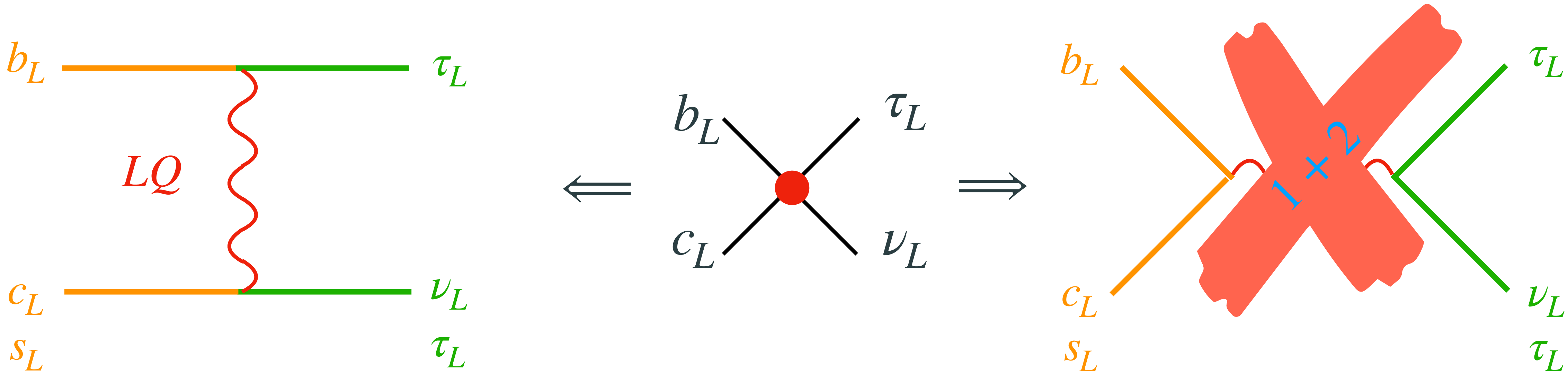


vs



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

Only leptoquarks are viable mediators!



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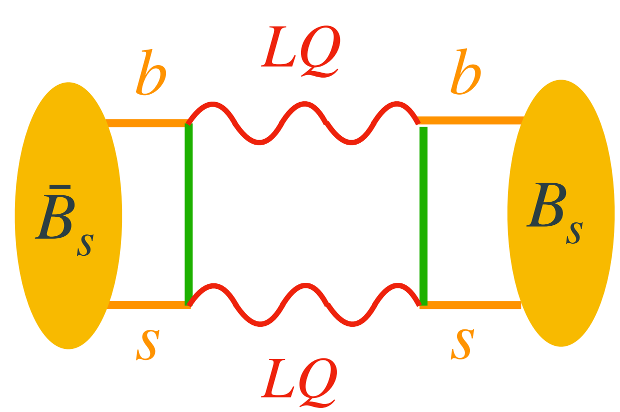

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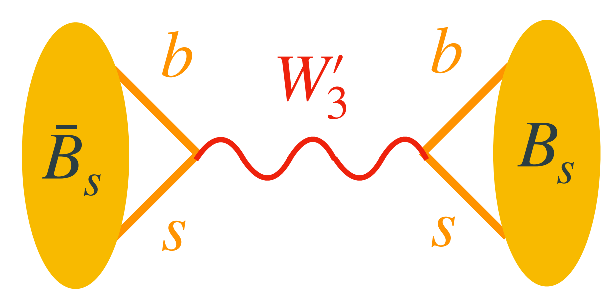

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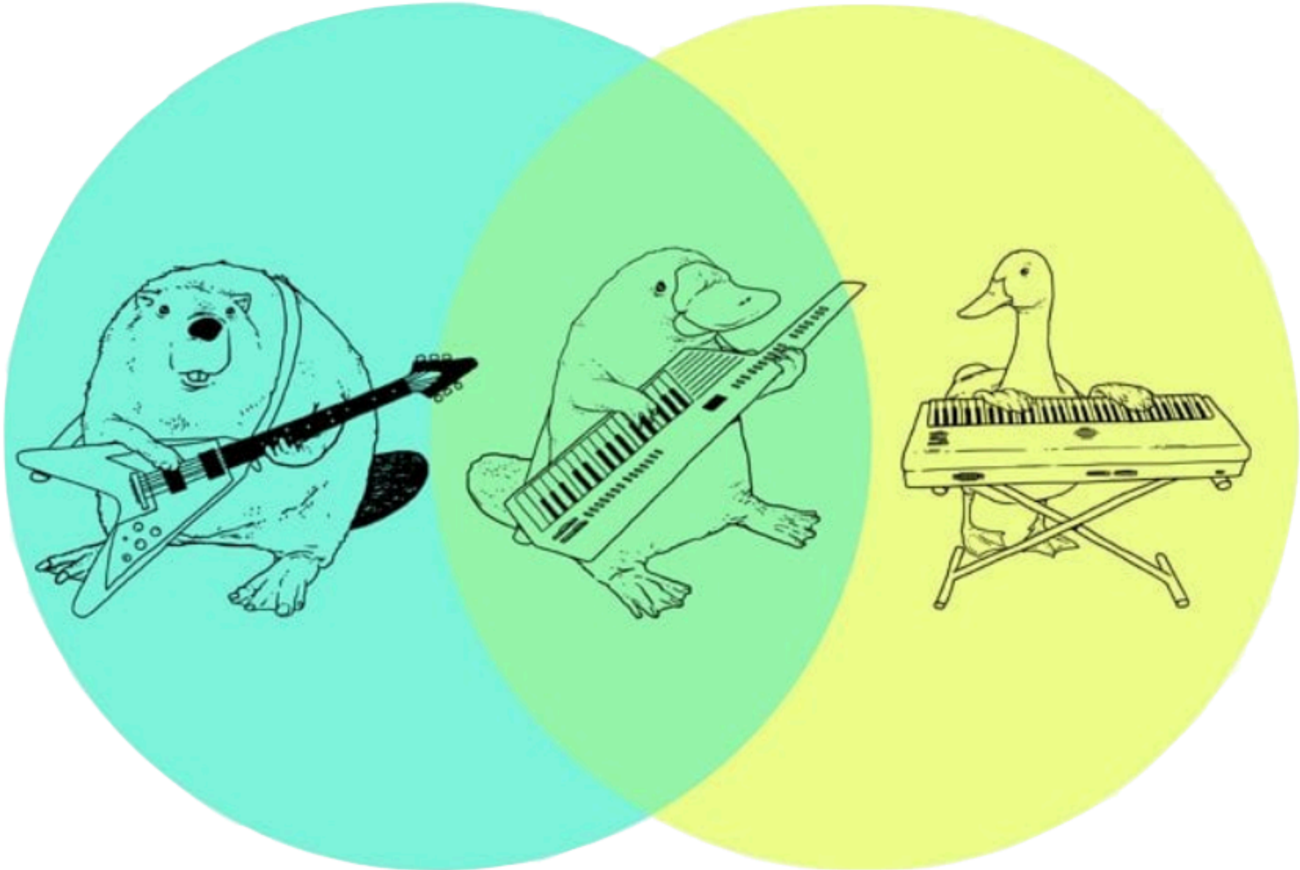
What is a leptoquark?



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	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
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]

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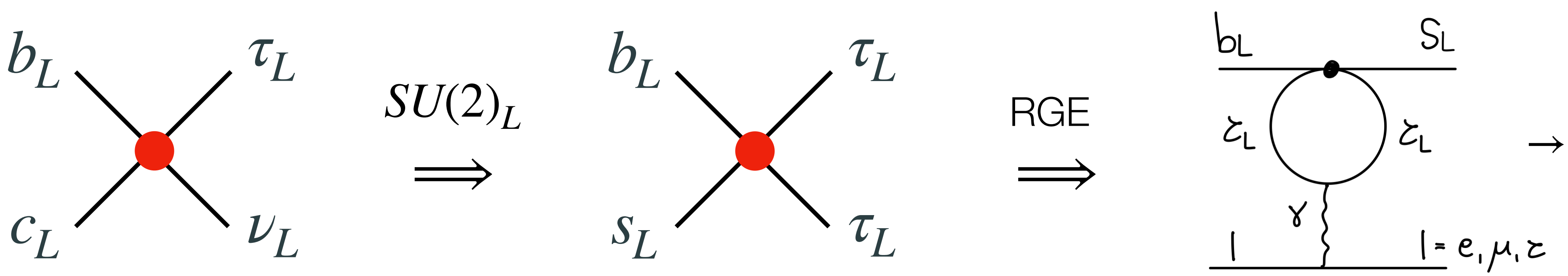
- Some (but not all) leptoquarks that explain the charged-current *B*-anomalies also give a *flavor universal* effect in $b \to s\ell\ell$ via RGE:



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

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

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

- 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 $\begin{cases} \text{ang. obs. in } B^{(0,+)} \to K^{*(0,+)}\mu^+\mu^- \\ \text{BRs of } B \to K\mu^+\mu^-, B \to K^*\mu^+\mu^-, B_s \to \phi\mu^+\mu^- \end{cases}$

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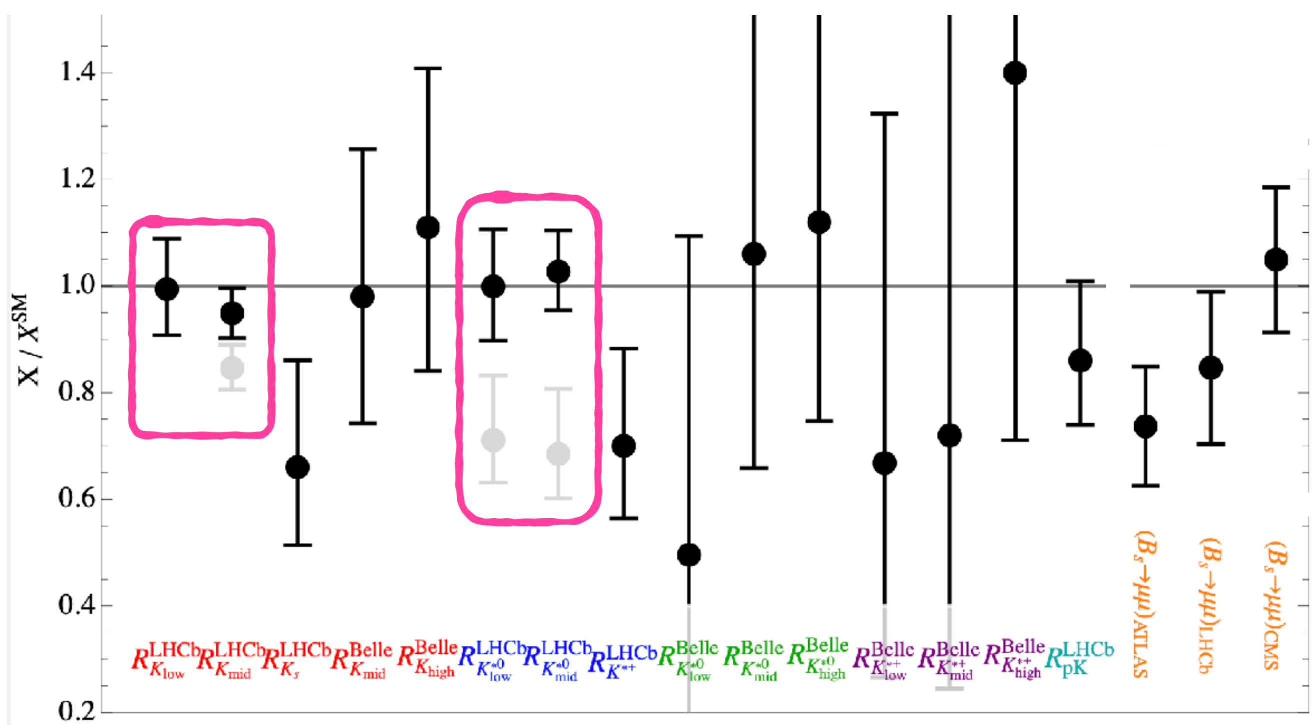
- 12/2022: a second LHCb analysis of R_K & R_{K^*} establishes μ/e lepton flavor universality in $b \to sll$ at $\sim 5\,\%$ level [LHCb,221209152]



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

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

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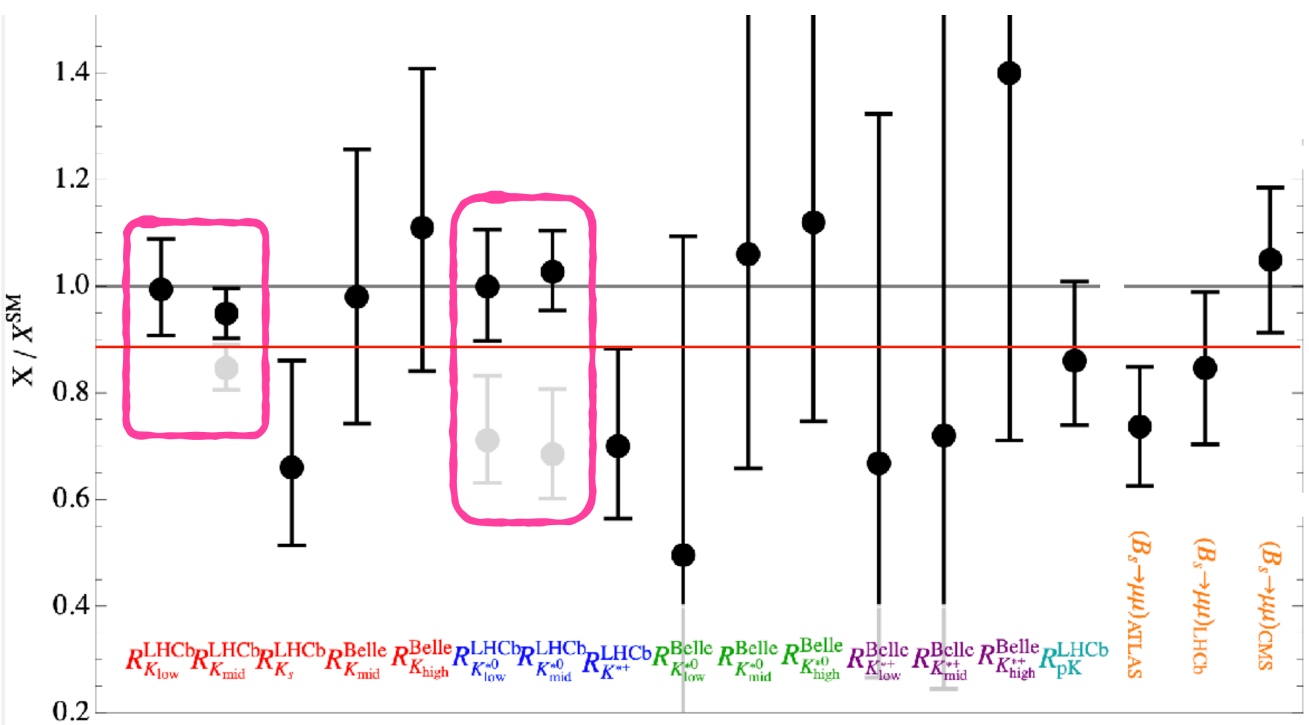

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- Still room for small μ/e lepton flavor violation at the $\sim 10\,\%$ level

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

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

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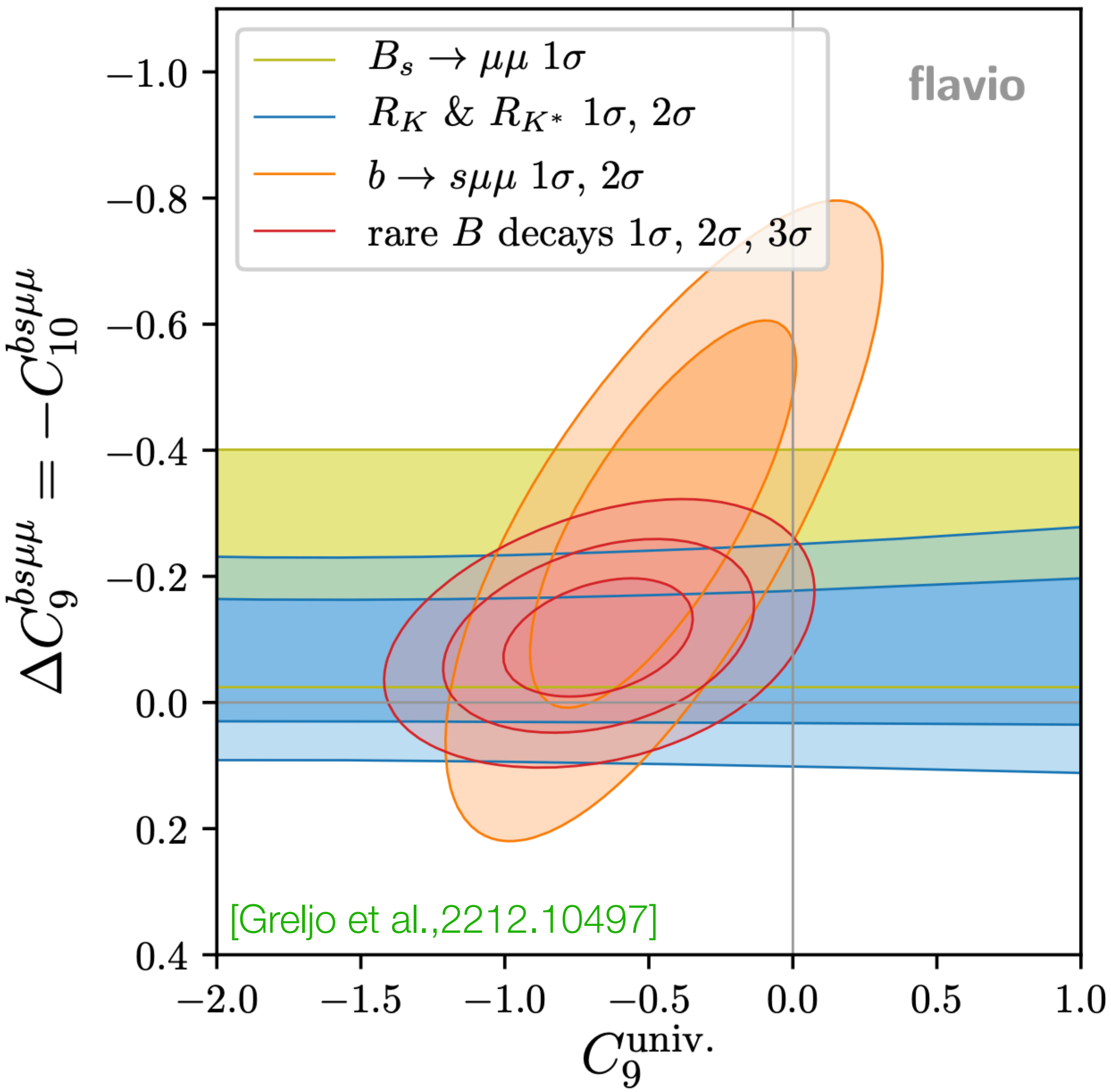

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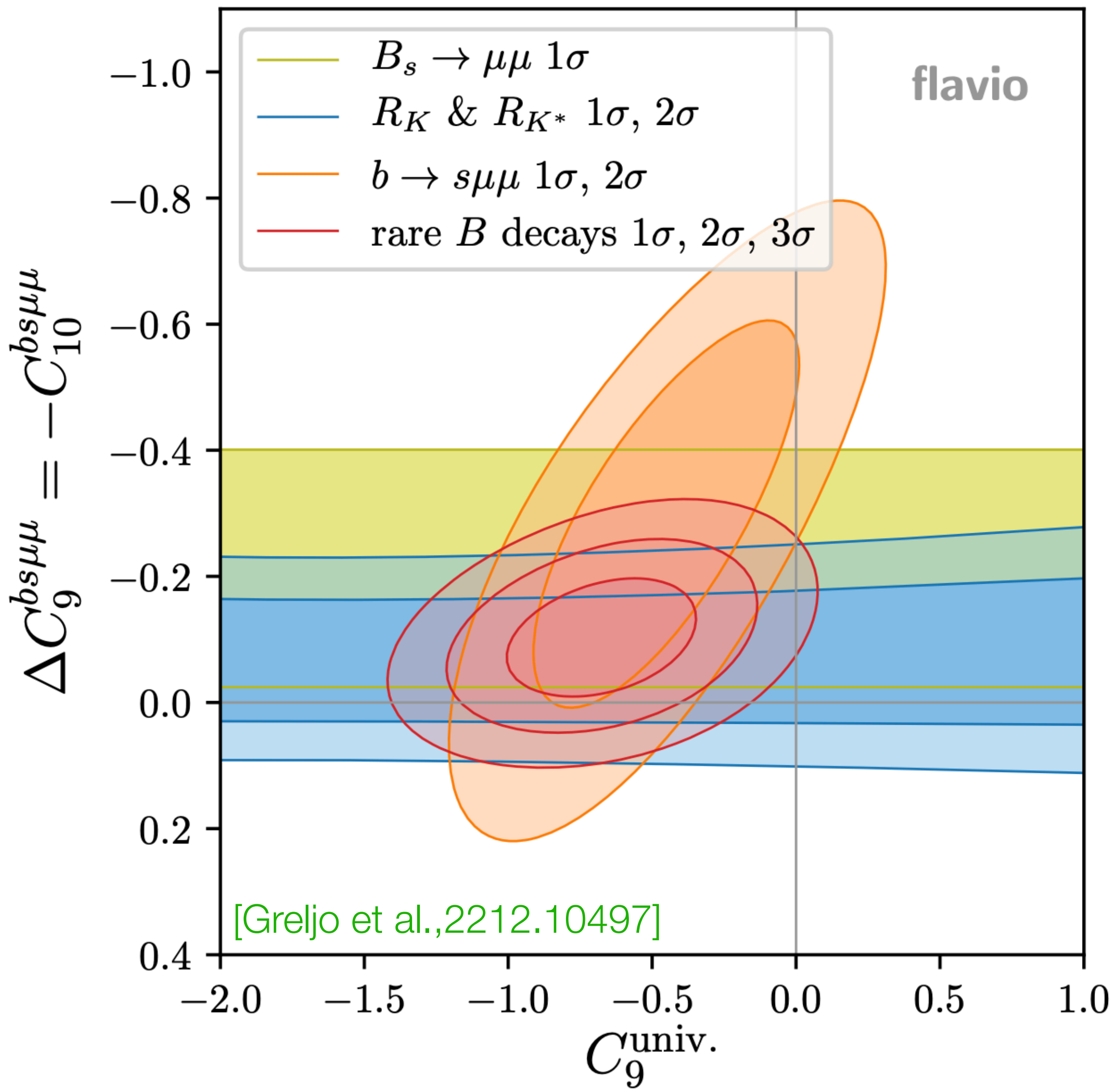

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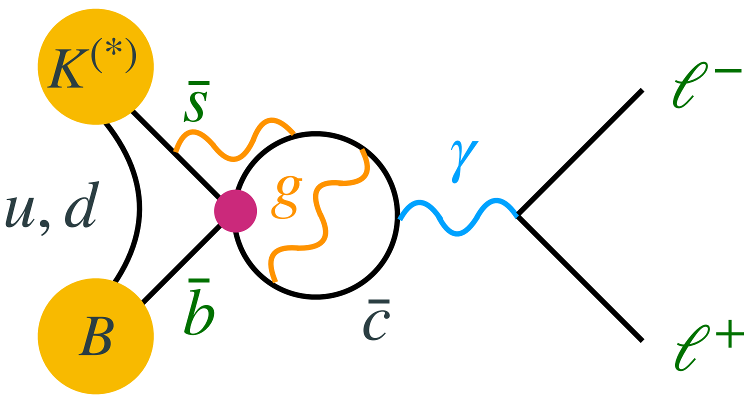
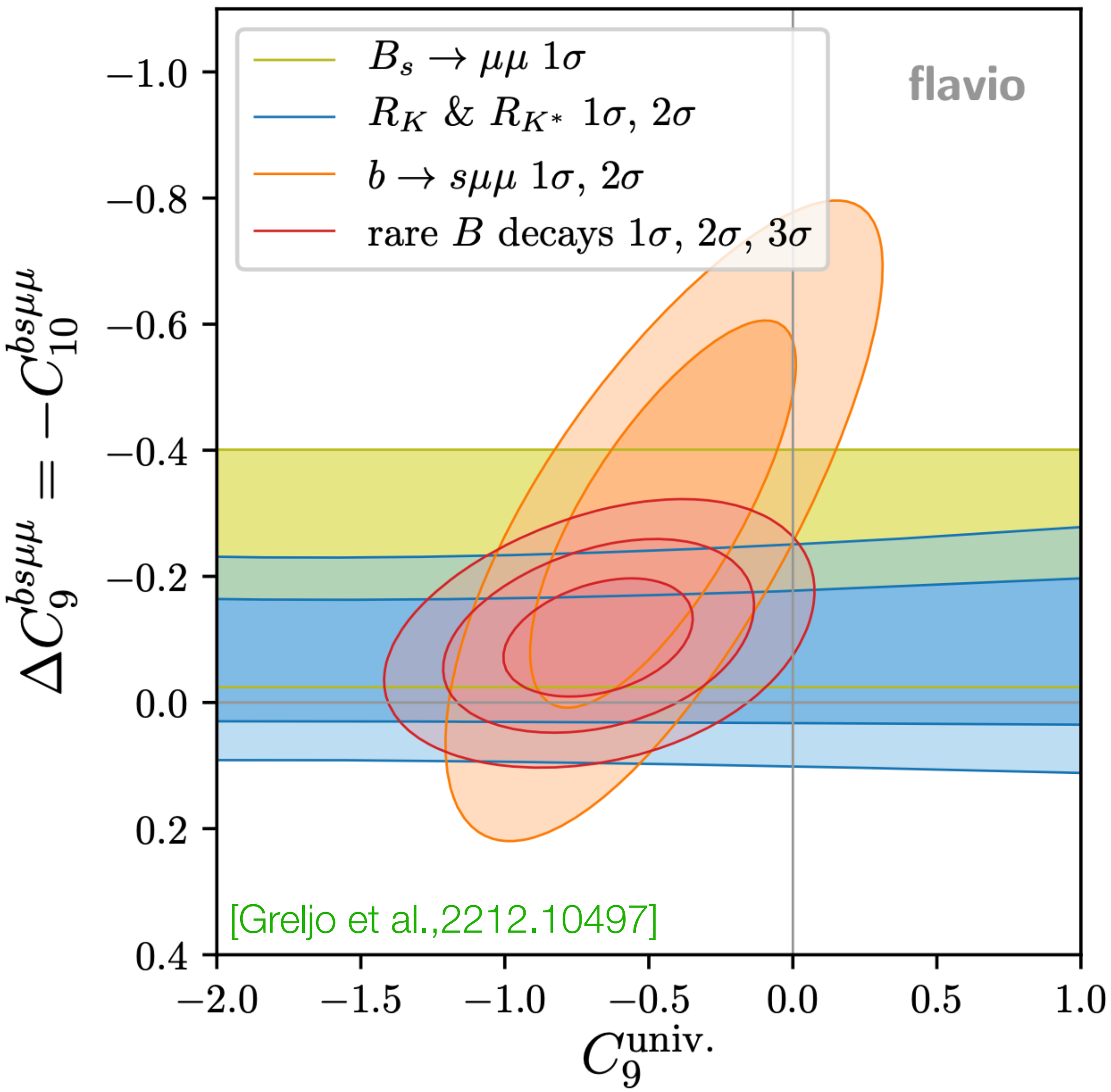
✳ But, non-trivial to distinguish from long-distance QCD ("charming penguins")





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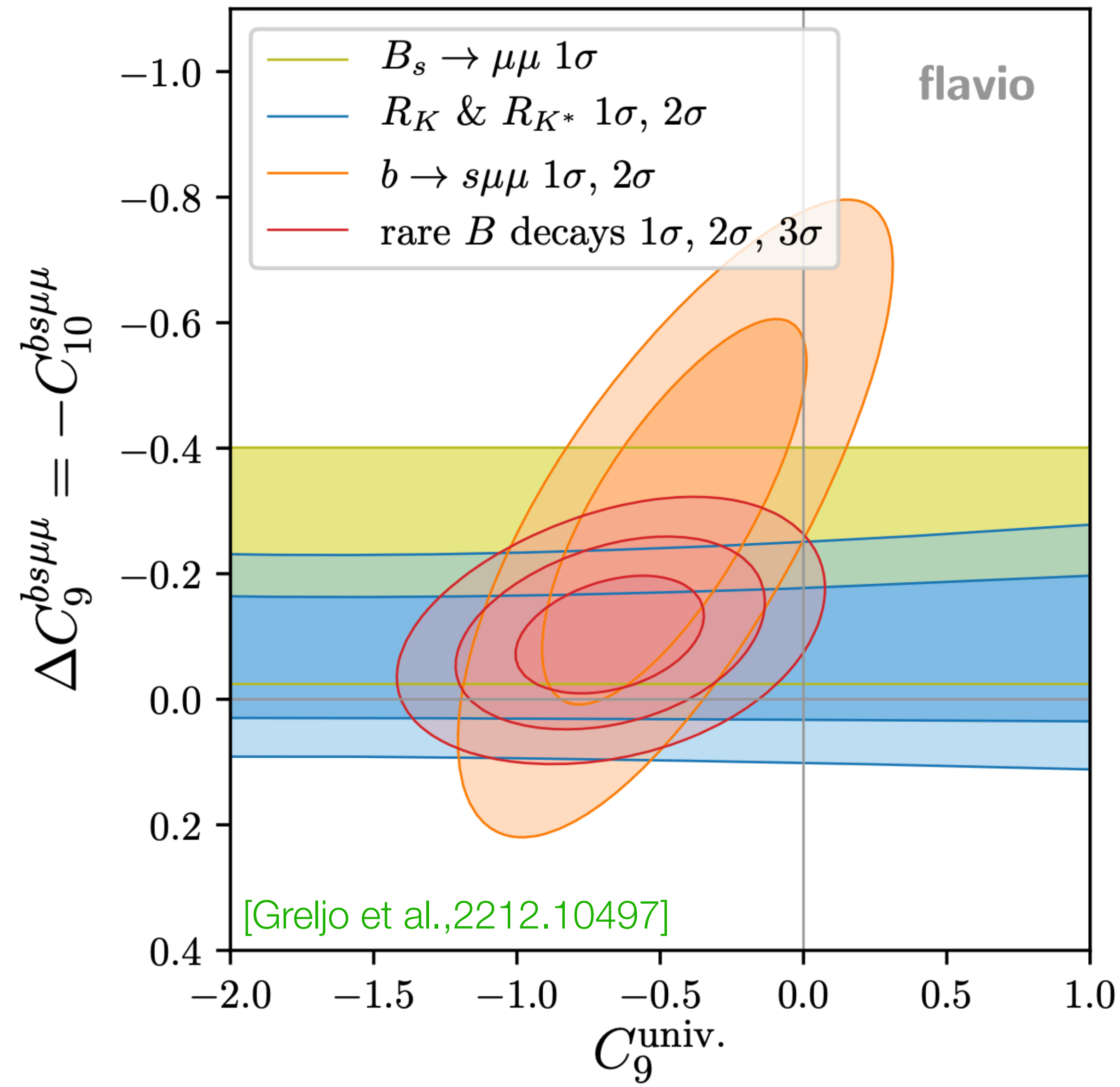

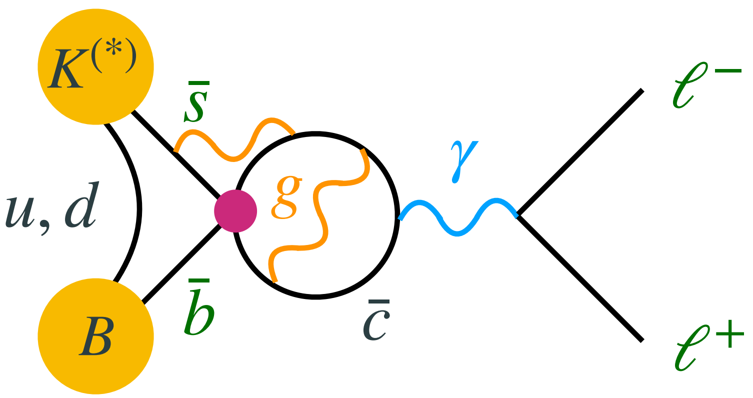

Currently, no agreement: need improvement on the theory side $\Longrightarrow$ [Gubernari et al. 2206.03797, Ciuchini et al. 2212.10516]

What changed? Implications for model building

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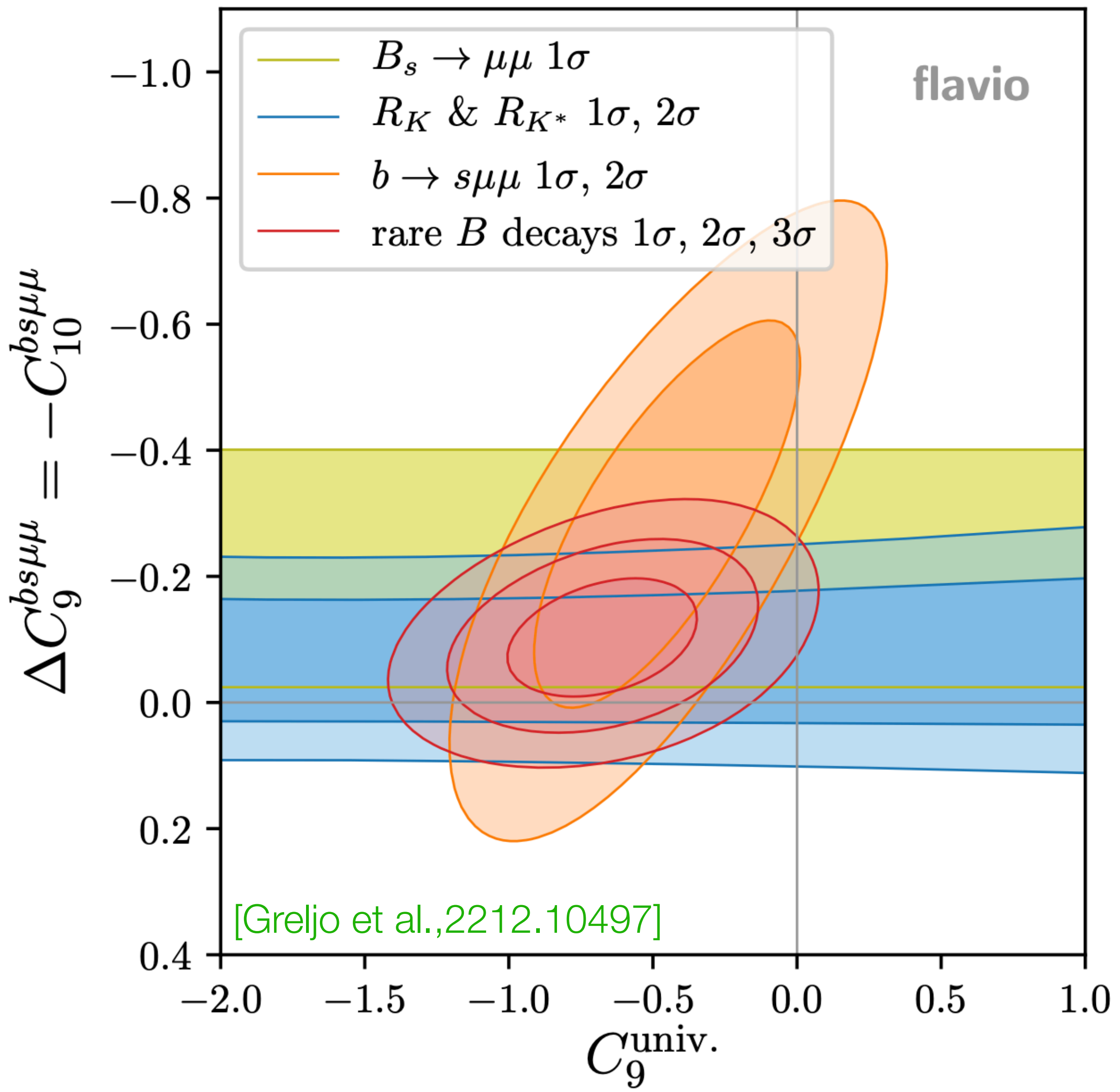

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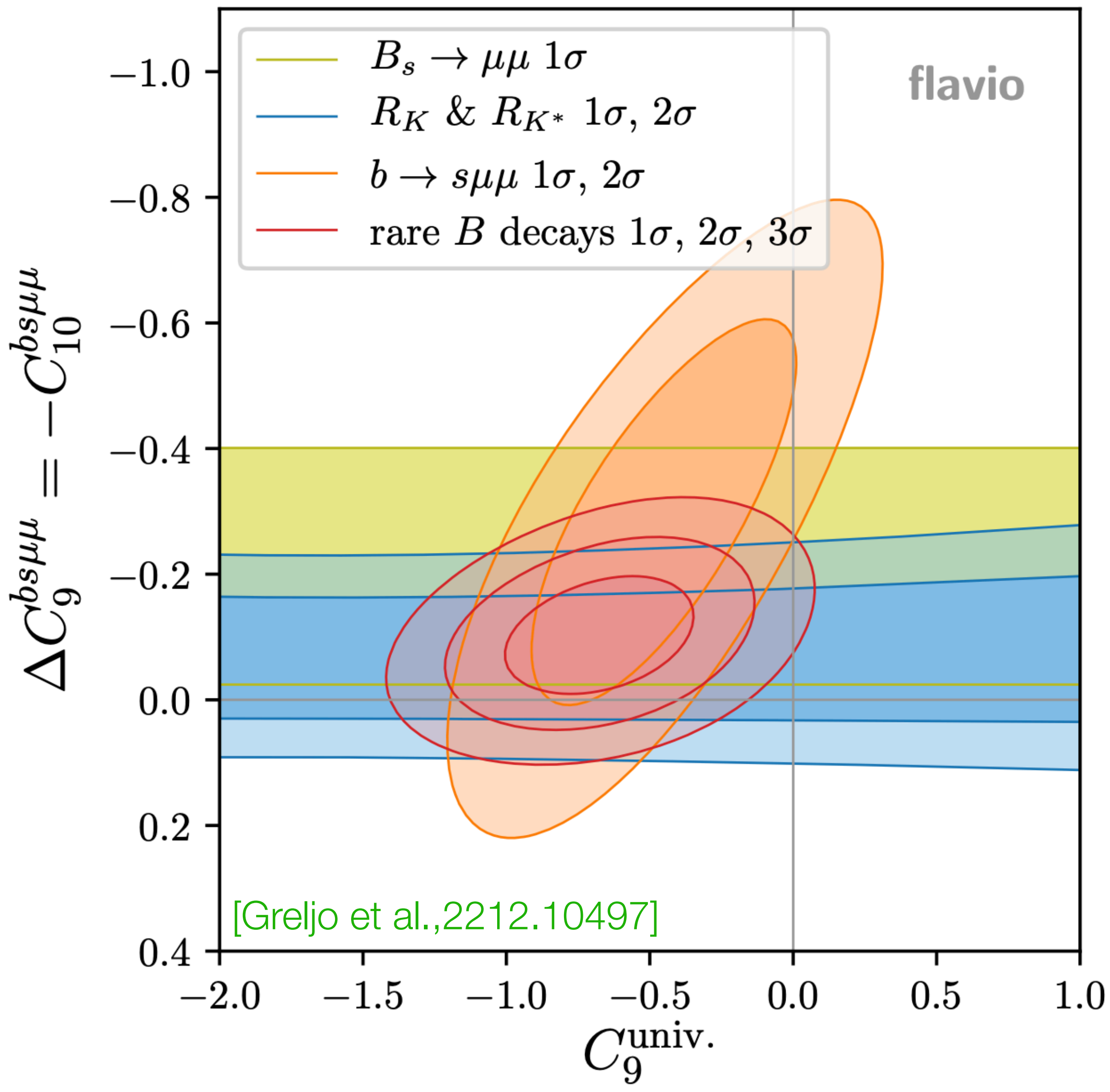

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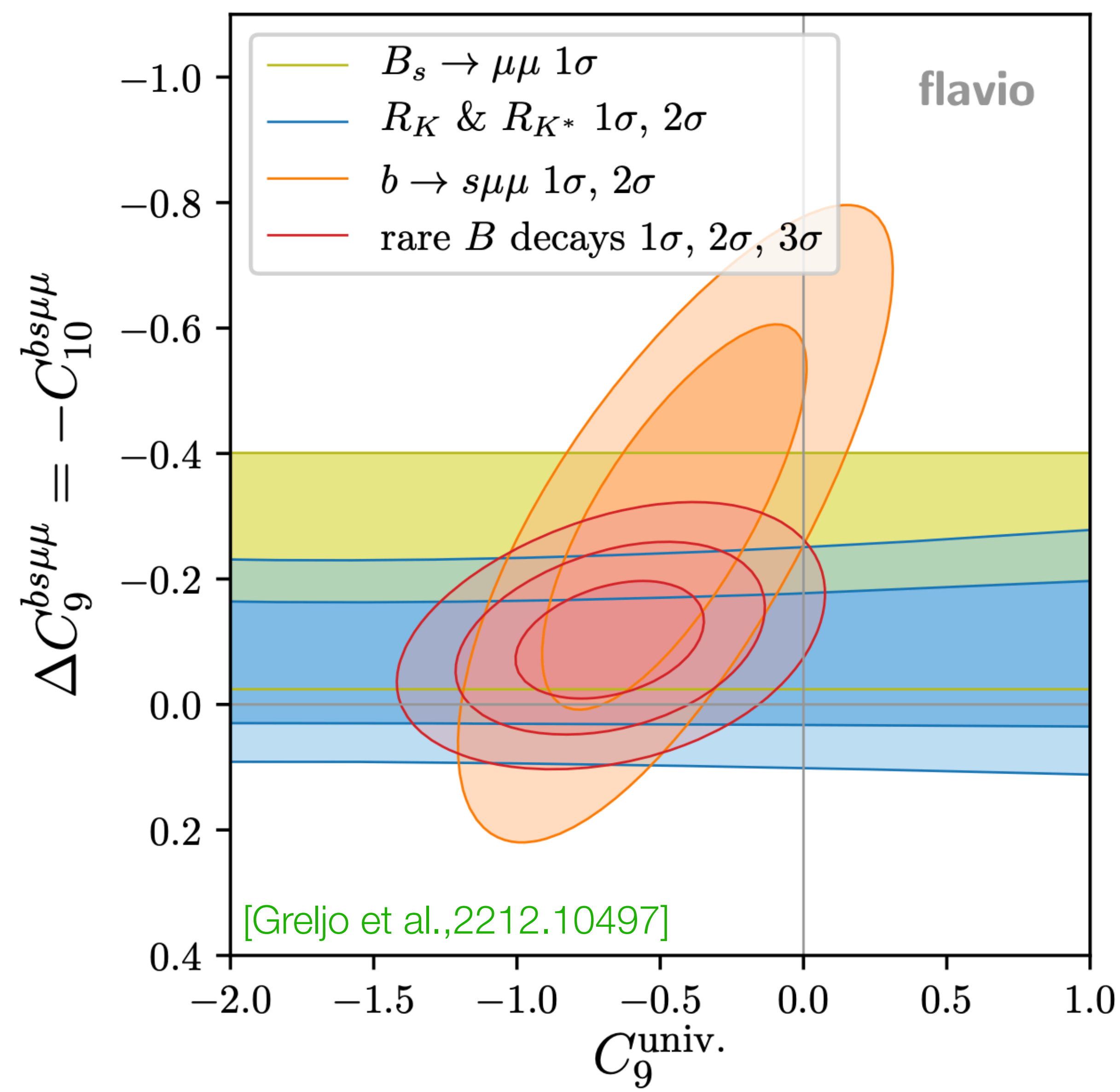
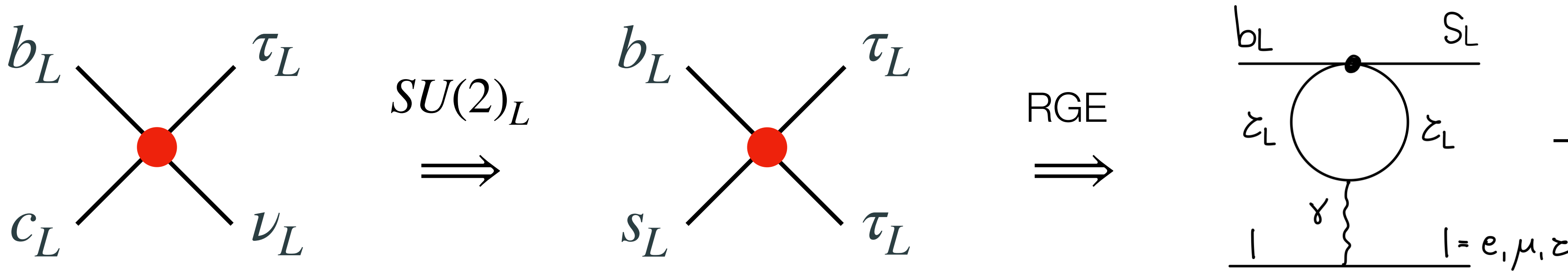
- Still interesting to consider models for $R_{D^{(*)}}$ (unaffected) that also give flavor universal contributions to the $b \to s\ell\ell$ system.



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:



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

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- 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]

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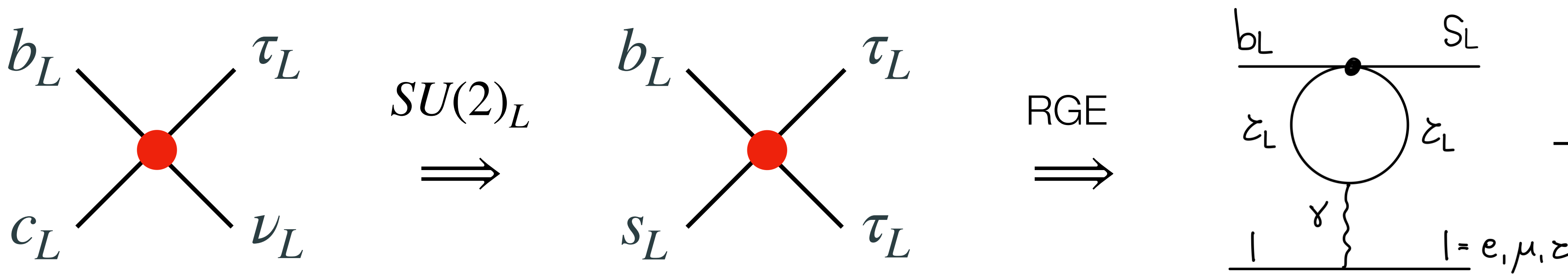

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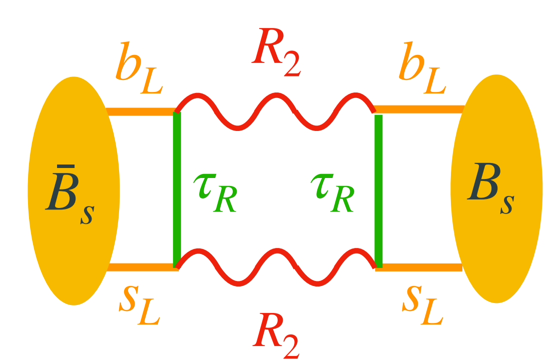
U_1	S_1	R_2
$C_{lq}^{(3)} = C_{lq}^{(1)}$	$C_{lq}^{(3)} = -\,C_{lq}^{(1)}$	Only $[C_{qe}]_{3333}$



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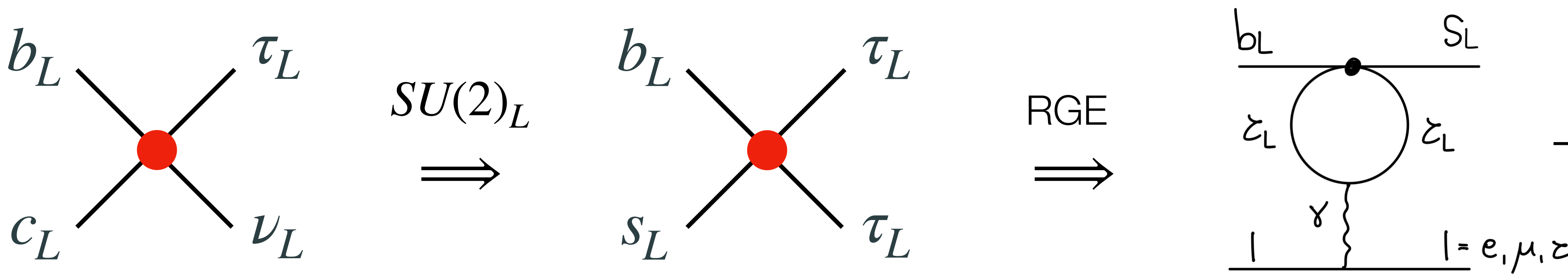

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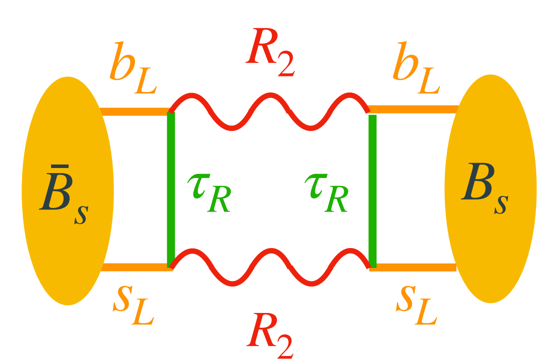

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Simplified model for U_1 leptoquark

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

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

U(2)-conserving U(2)-breaking U(2)-conserving

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U(2)-conserving — U(2)-breaking — U(2)-conserving

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

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

U(2)-conserving — U(2)-breaking — U(2)-conserving

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

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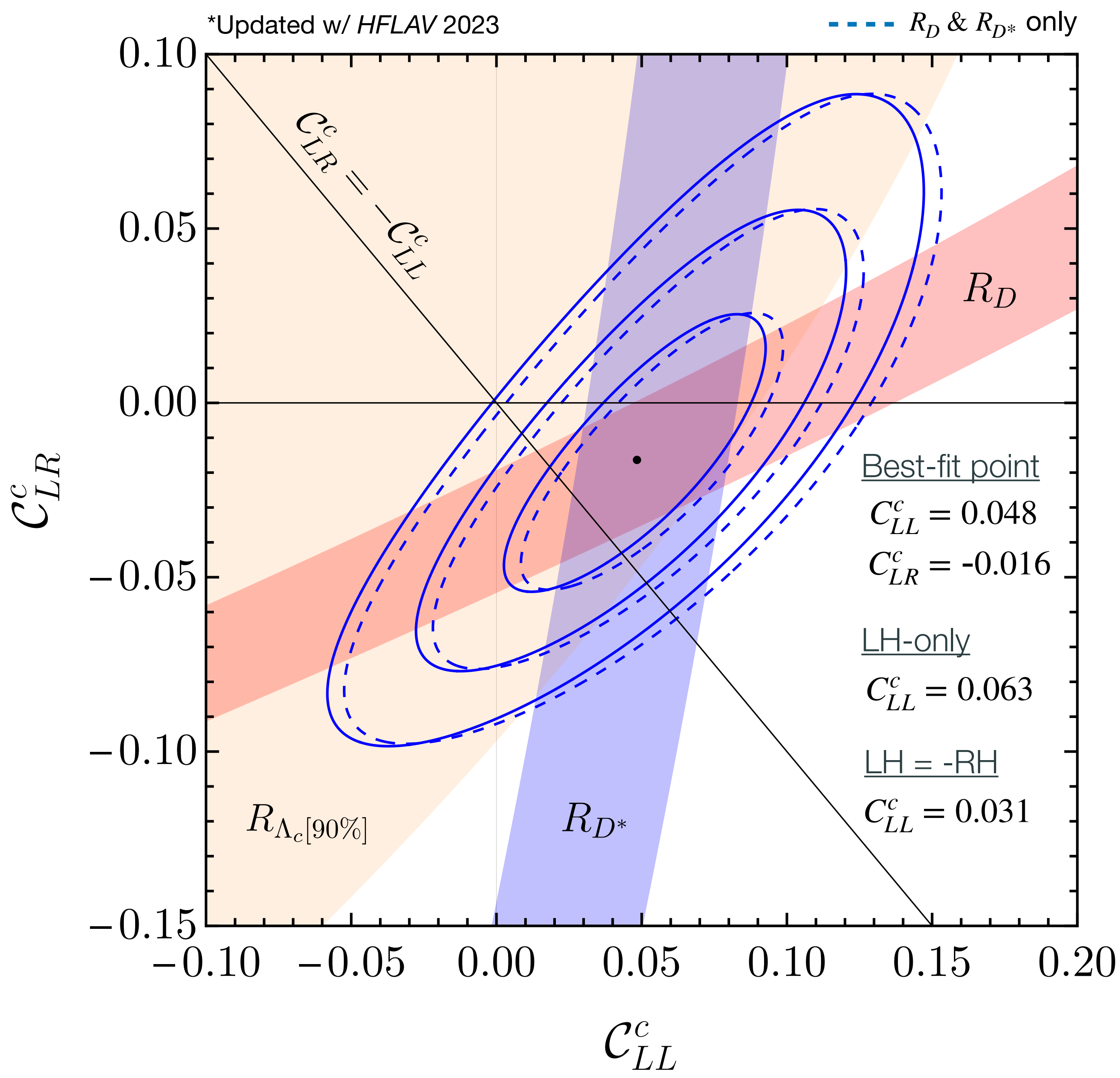
$$\mathcal{L}_{b\to c\tau\bar{\nu}} = -\frac{2}{v^2} V_{cb}\left[\left(1 + C^c_{LL}\right)(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu \nu_L) - 2\, C^c_{LR}\,(\bar{c}_L b_R)(\bar{\tau}_R\,\nu_L)\right]$$



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

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

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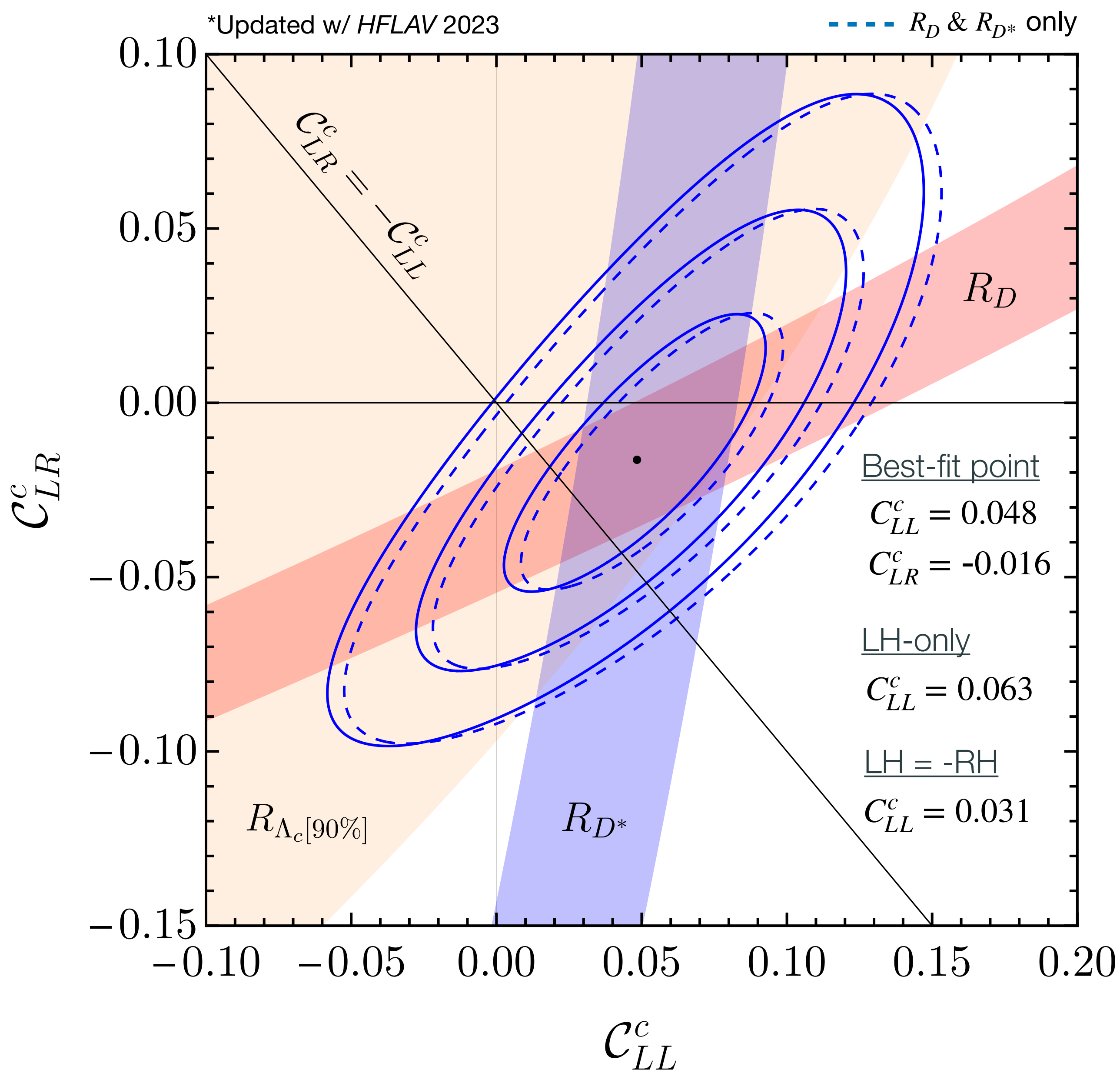

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Matching: NP scale and U(2)-breaking

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

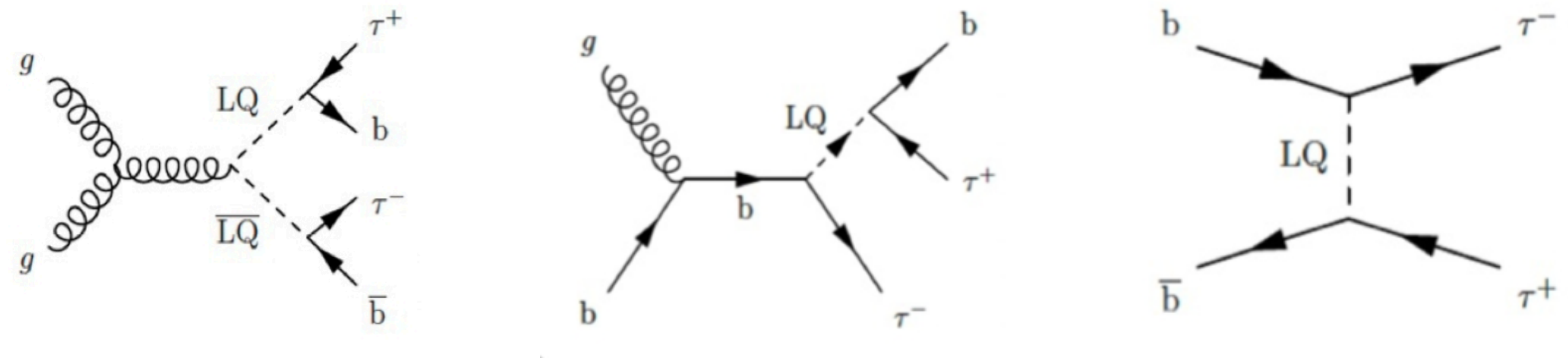
New physics scale preferred by low-energy fit:

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

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

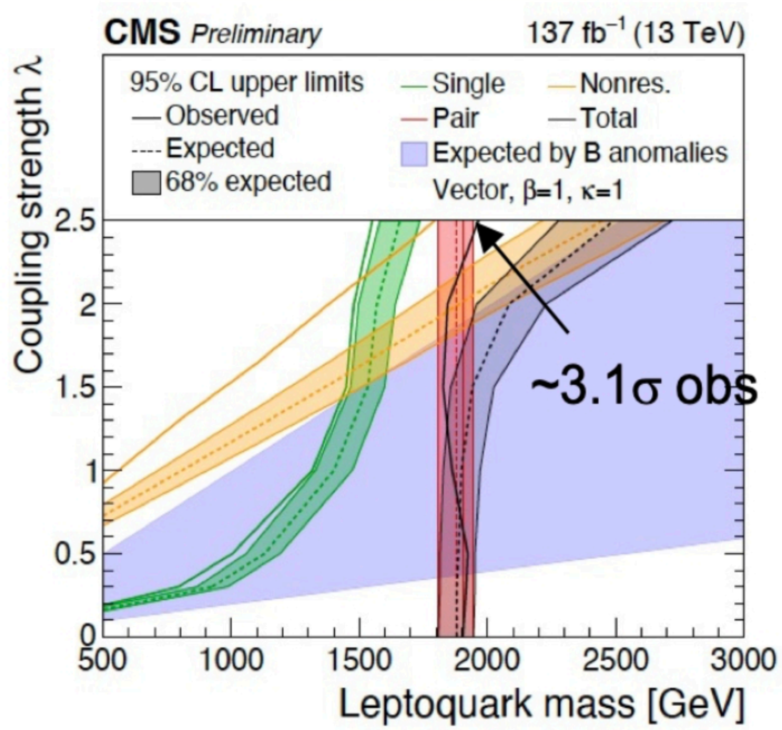
[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, 2210.13422]

High-energy searches: U_1 leptoquark

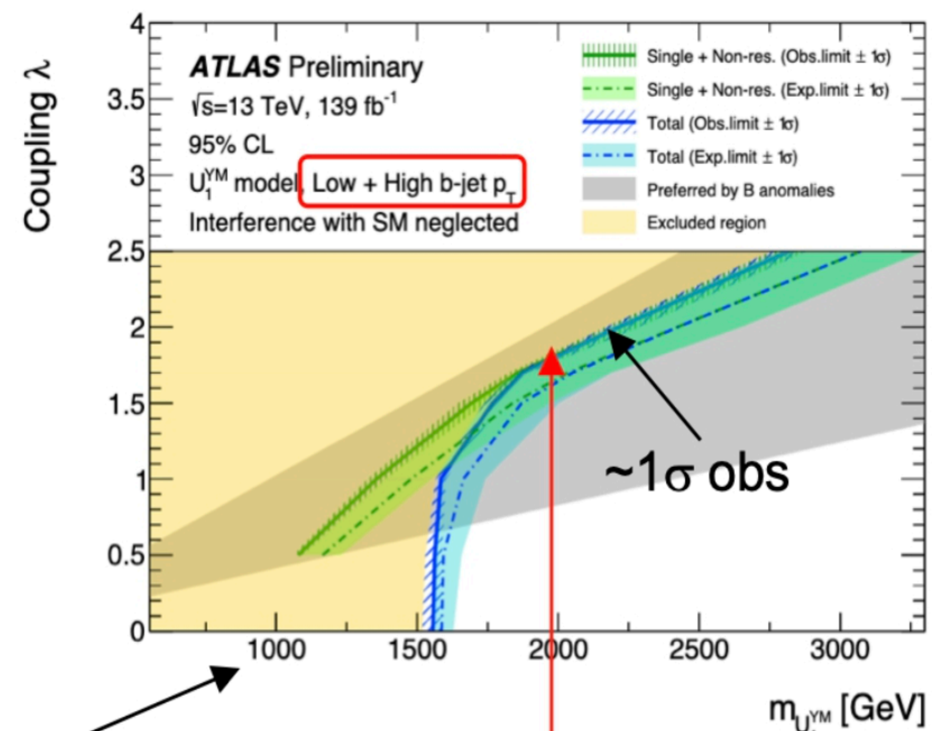


Caveat: BR=1 (CMS) vs BR=0.5 (ATLAS)

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



EXOT-2022-39



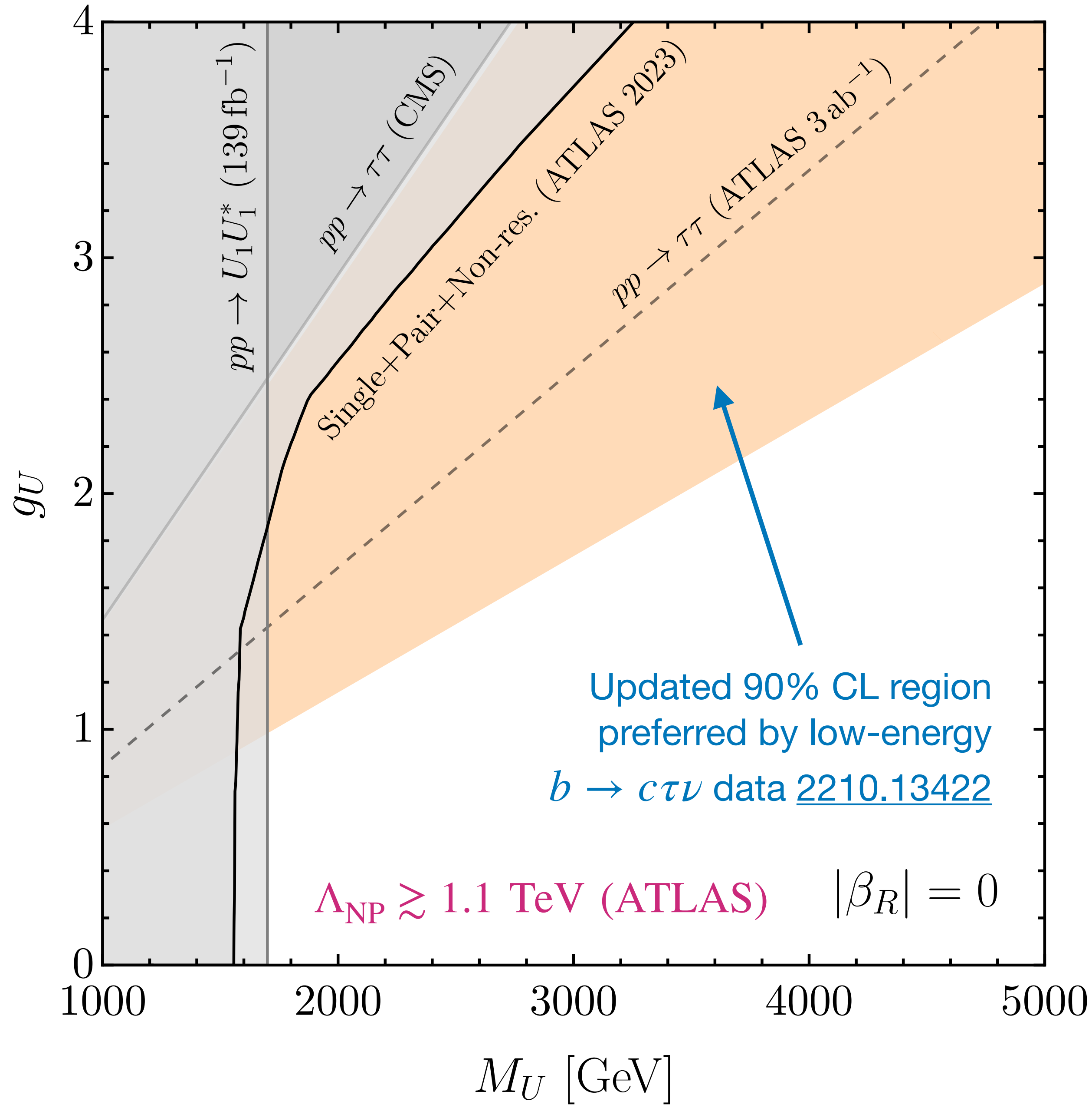
Large improvement in sensitivity
when adding low b-jet p_T category

Excludes CMS' excess

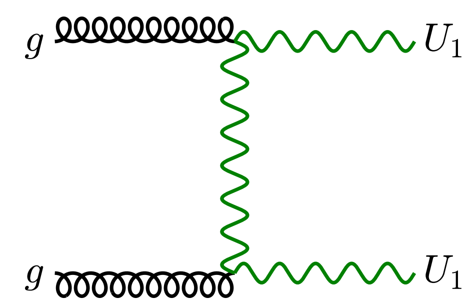
[A. Juste, Moriond EW '23]

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



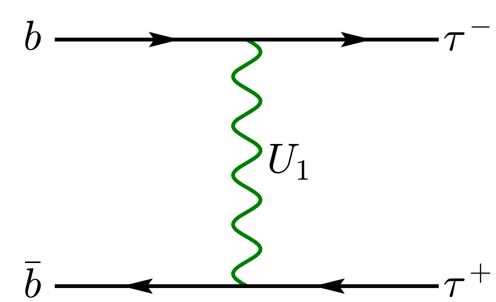
$U_1 \to b\tau^+, t\bar{\nu}$

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

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

2012.0417

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



2002.1222

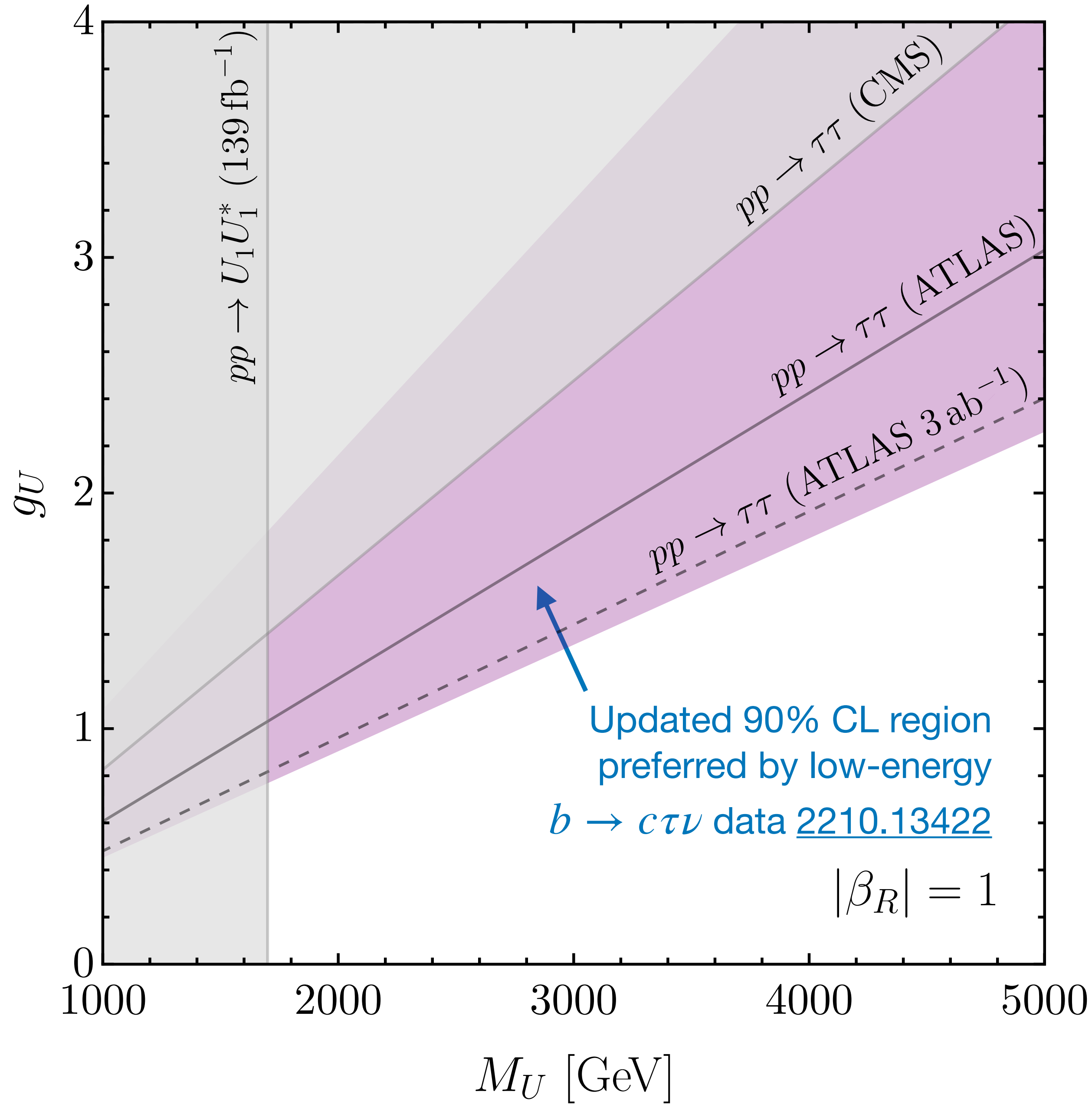
High mass Drell-Yan tails

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

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

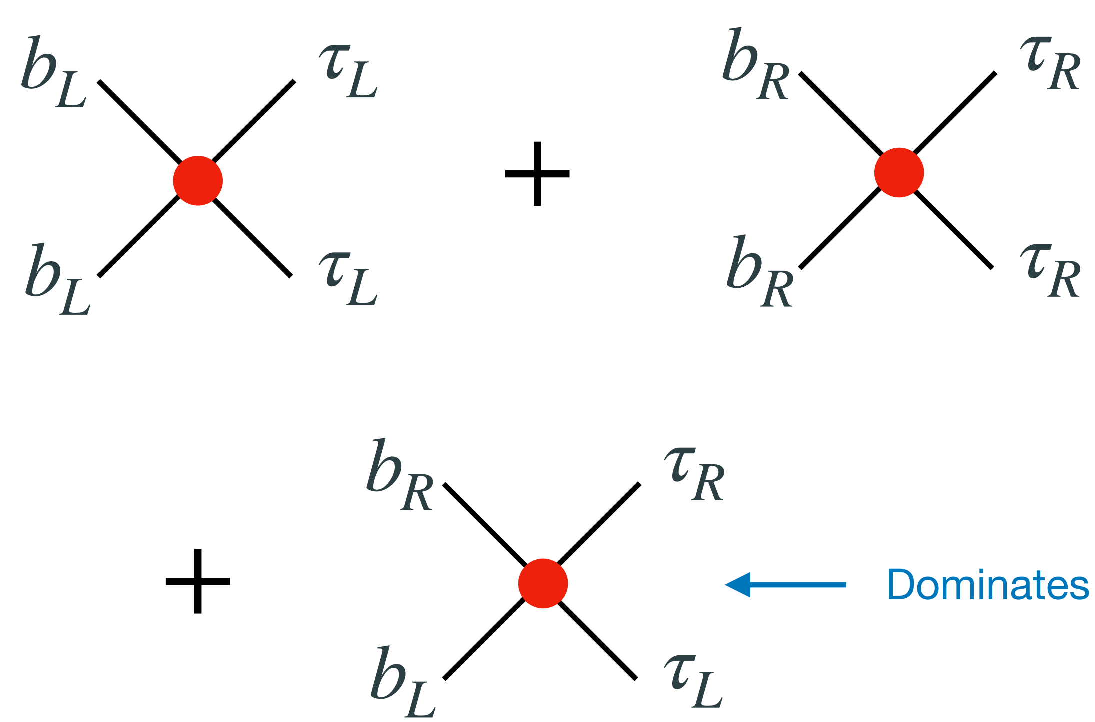
High-energy searches: U_1 leptoquark model (L&R)

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



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

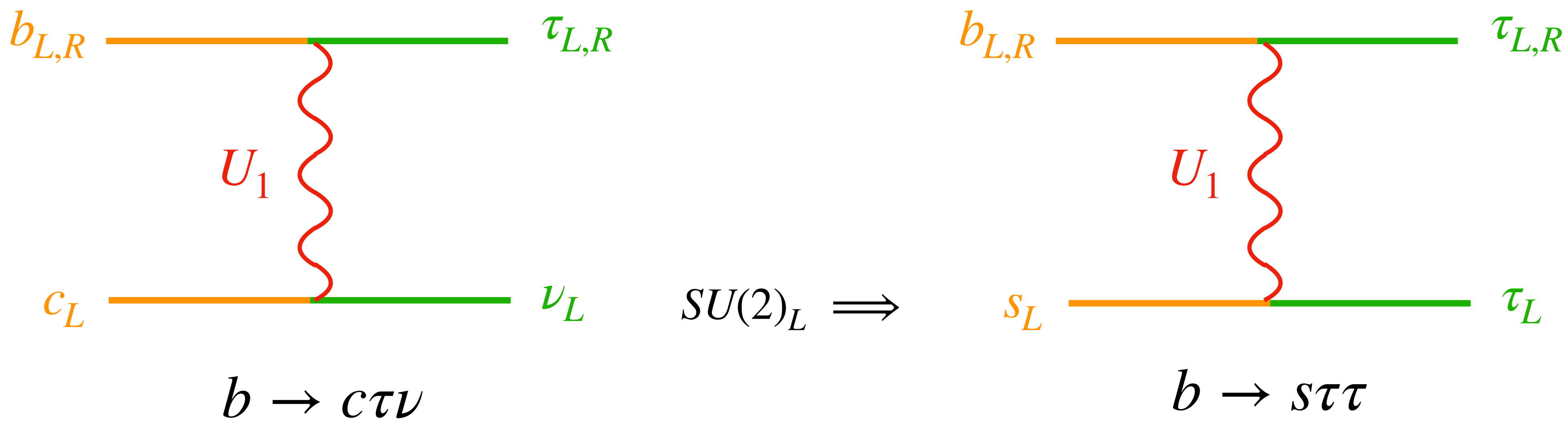
- Additional contributions give stronger bound from t-channel Drell-Yan $\tau\tau$:



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

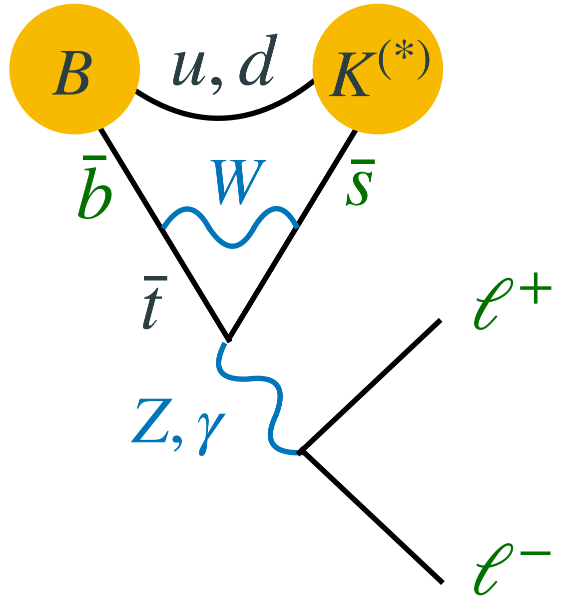
U_1 connects $R_{D^{(*)}}$ to $b \to s\tau\tau$ observables

- 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 $b \to s\tau\tau$!

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



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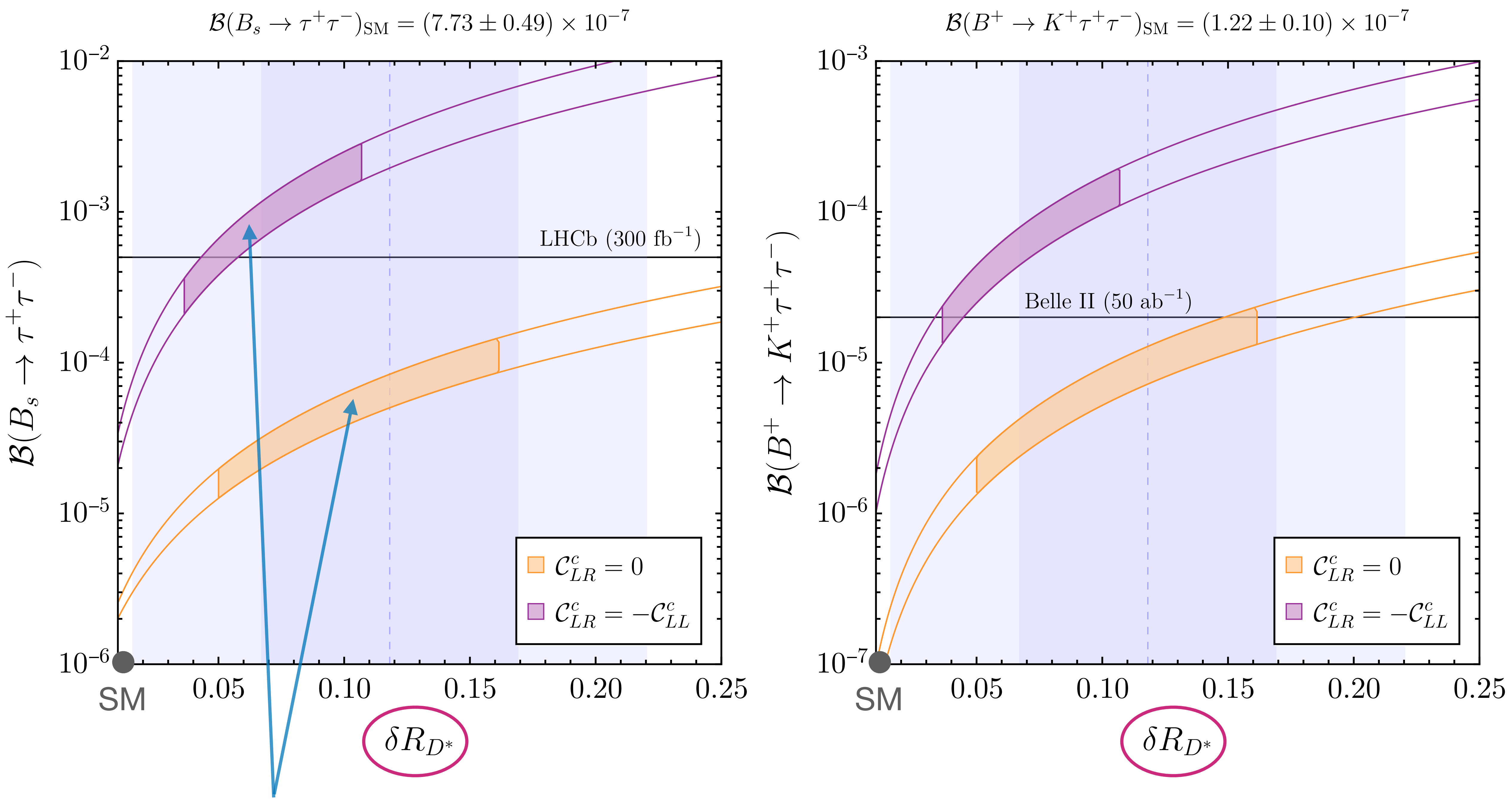
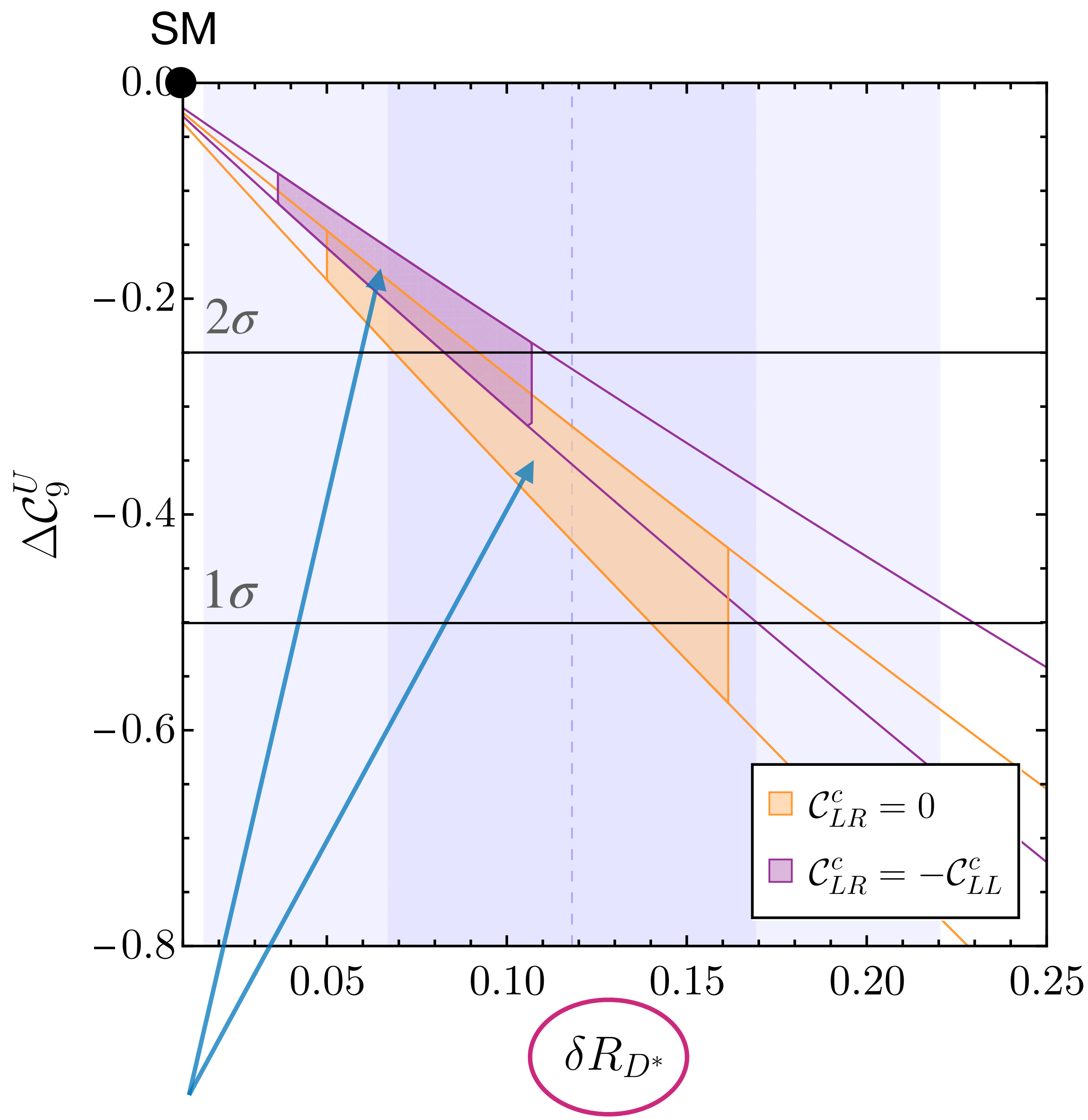


[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, 2210.13422]

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 $b \to s\ell\ell$!



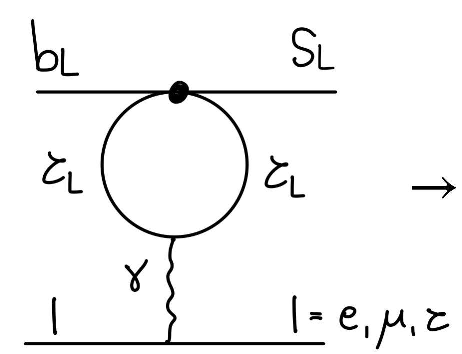
Updated 90% CL region preferred by low-energy $b \to c\tau\nu$ data 2210.13422

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

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

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

RGE $\Longrightarrow$



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

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

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

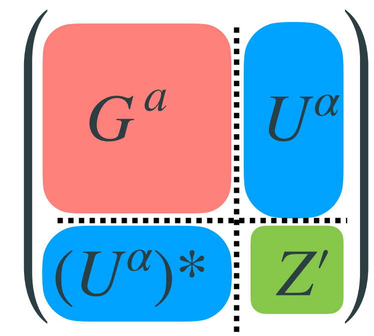
[Altmannshofer, Stangl 2103.13370
Bobeth, Haisch, 1109.1826; Crivellin et al., 1807.02068;
Algueró et al., 1809.08447]

UV Completion for the U_1 Leptoquark

UV Model: New flavor non-universal gauge interactions

Based on "4321" gauge symmetry:

$SU(4) \sim$



$U(1)_Y$

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

$SU(3)_c$

UV Model: New flavor non-universal gauge interactions

Based on "4321" gauge symmetry:

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

$U(1)_Y$

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$SU(3)_c$

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

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

- 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: New colored particles and EW observables

- In addition to the U_1 LQ, we also get neutral G', Z' vectors.
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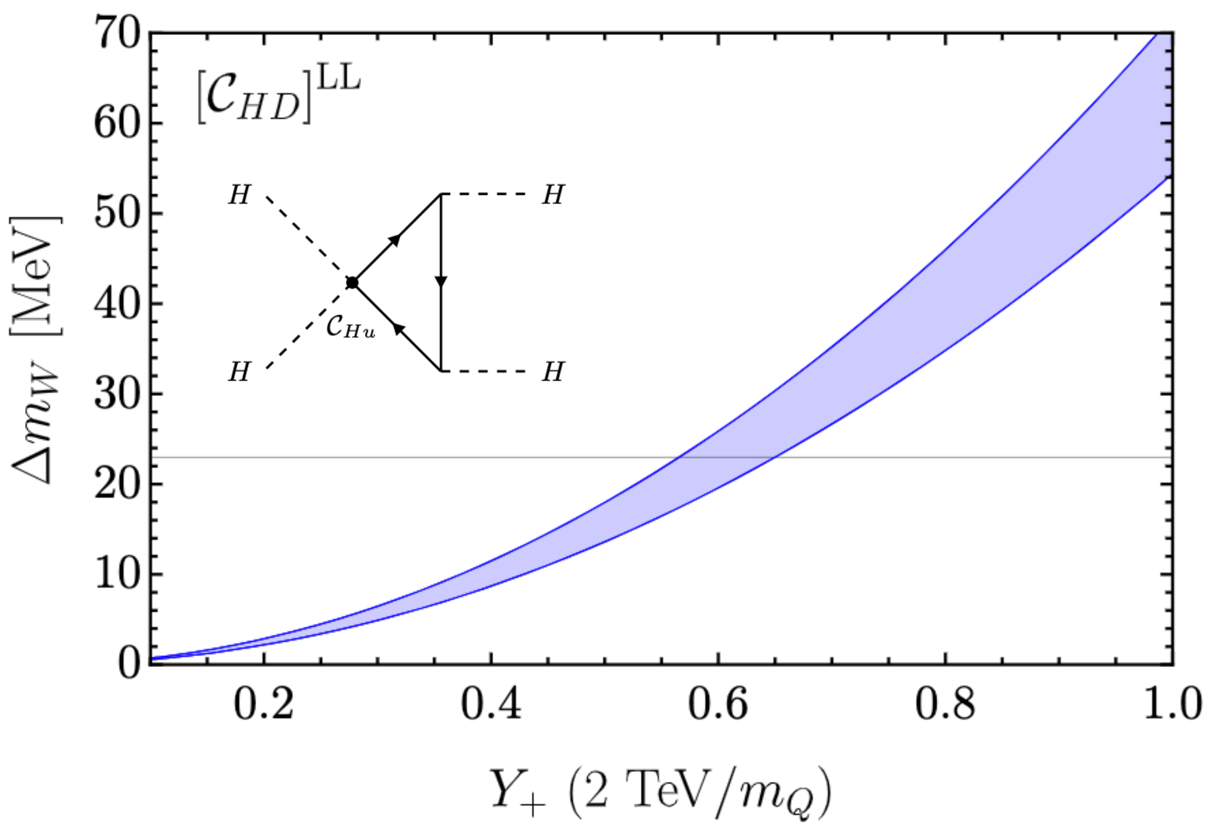
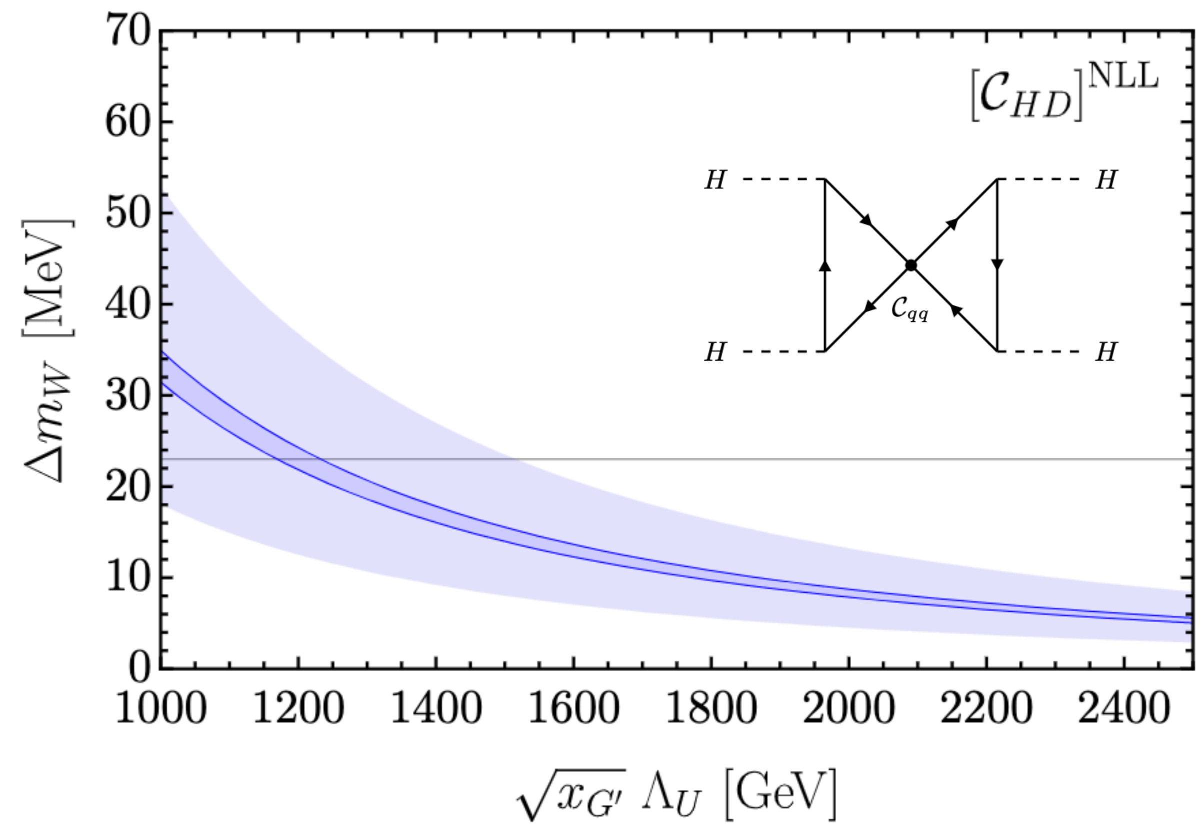
UV Model: New colored particles and EW observables

- 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.

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

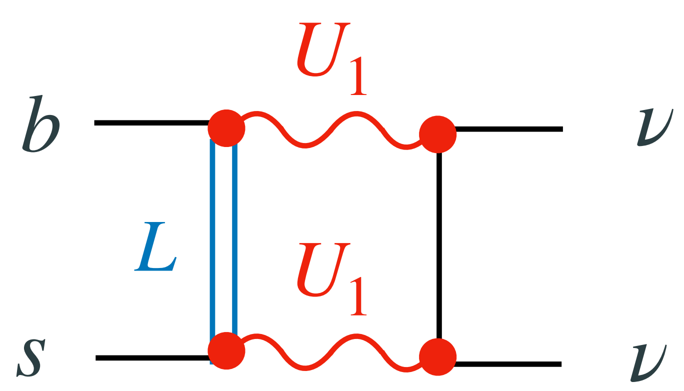


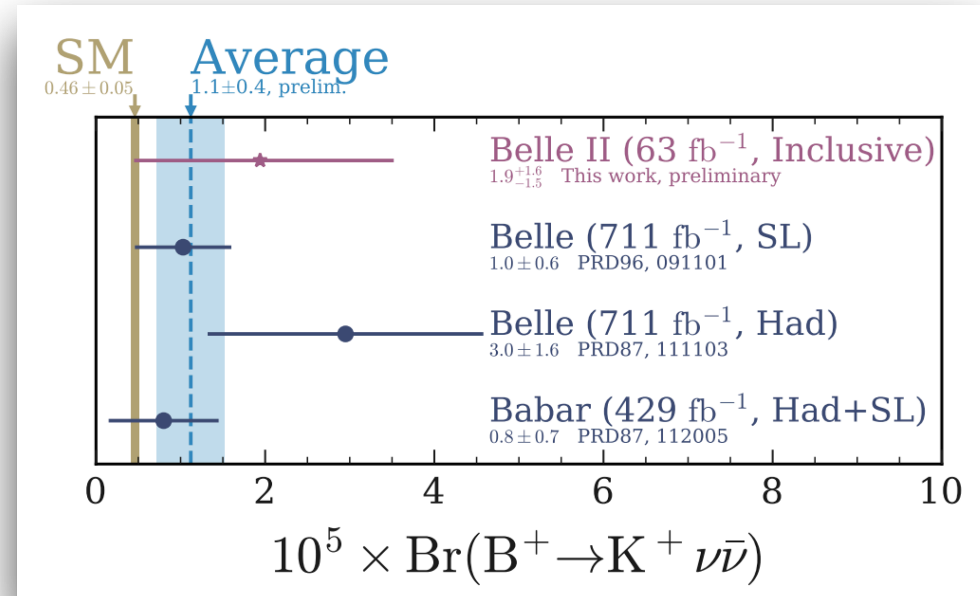


- Full EW fit in 4321 model: [Allwicher, Isidori, Lizana, Selimovic, BAS, 2302.11584]

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

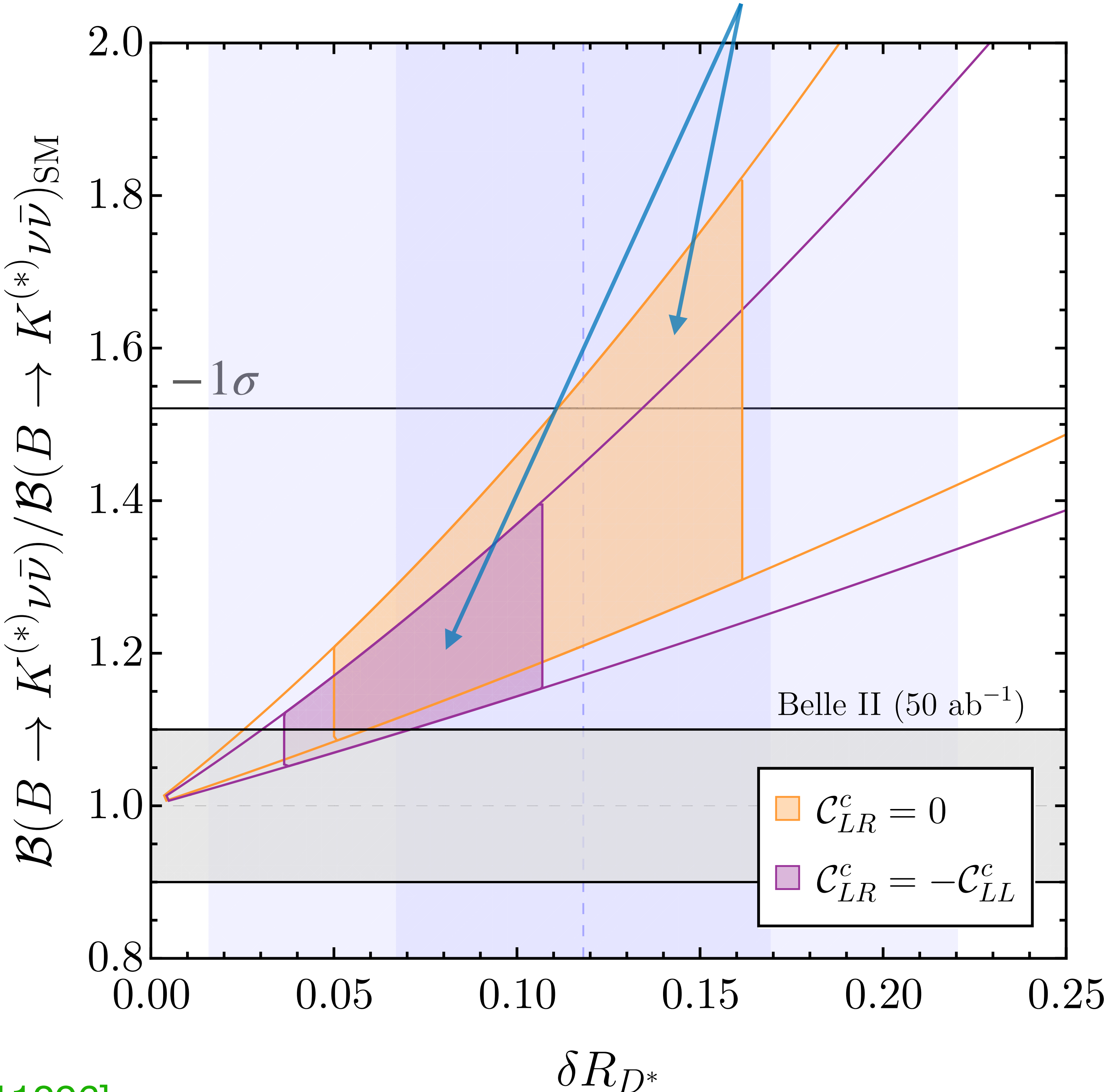
- Some (important) effects appear only at one loop. For U_1, requires UV model!





[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]

Conclusions

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Thanks a lot for your attention!

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