Connecting B anomalies and τ observables

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Vienna, 6-8.09.2021

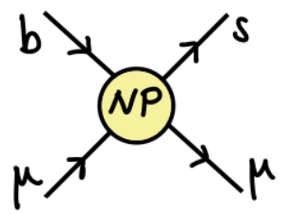
Intro

If the anomalies in $b \to sll$ and $b \to c\tau\nu$ are NP signals, **where else** can we expect to see deviations from the SM?

- obs. in the same partonic transition: angular obs. in $B \to D^{(*)}$
  other LFU ratios (R_ϕ , $R_{J/\psi}$...)
- obs. with a different quark flavor in the final state: $b \to dll$,$b \to ul\nu$
- obs. with τ leptons LFU tests in τ decays,
  $b \to s\tau\tau, pp \to \tau\tau$
  τ/μ LFV ($\tau \to \mu\phi, \tau \to \mu\gamma, b \to s\tau\mu$)
- $B \to K\nu\bar{\nu}$...

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

$\boldsymbol{b \to sll}$ $\quad \mathcal{O}_{9-10} = (\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L)$ (or $\mathcal{O}_9$)



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

- direct production possibly out of reach, but good chances for indirect discovery
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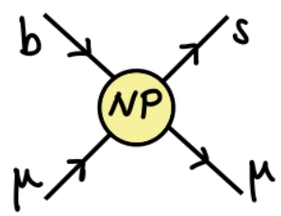

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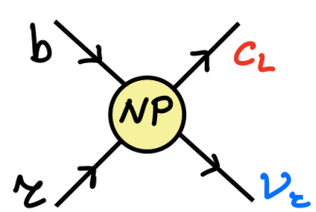
$\boldsymbol{b \to c\tau\nu}$ $\quad \mathcal{O}_{V_L} = (\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_L)$ and or $\mathcal{O}_{S_R}/\mathcal{O}_{S_L}, \mathcal{O}_T$



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

- large effects in both low- and high-energy observables around the corner
- mediators: leptoquarks (U_1, S_1, R_2)

Towards a combined explanation

To explain both anomalies, NP must be:

- ~ TeV
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Variations with RH currents also possible.

$$\mathscr{L} = -\frac{1}{v^2}\left(C_{lq}^{(3)}(\bar{l}_L\gamma^\mu\tau^a l_L)(\bar{q}_L\gamma^\mu\tau^a q_L) + C_{lq}^{(1)}\,(\bar{l}_L\gamma^\mu l_L)(\bar{q}_L\gamma^\mu q_L)\right)$$

- reproduces known EFT solutions: $C_9^\mu = -\,C_{10}^\mu$ for $b \to sll$, V_L for $b \to c\tau\nu$
- need $C_{\ell q}^{(3)} \approx C_{\ell q}^{(1)} \equiv C_{LL}$ to avoid too large $b \to s\nu\bar{\nu}$.

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If $R_{D^{(*)}}$ is due to NP, the same NP has to show up somewhere in τs:

LFUV in τ decays

LFV in τ and B decays
$(\tau \to \mu\phi, \tau \to \mu\gamma, b \to s\tau\mu)$

$B \to K\tau\tau, B_s \to \tau\tau$

$pp \to \tau\tau$
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Implications of $R_{D^{(*)}}$

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

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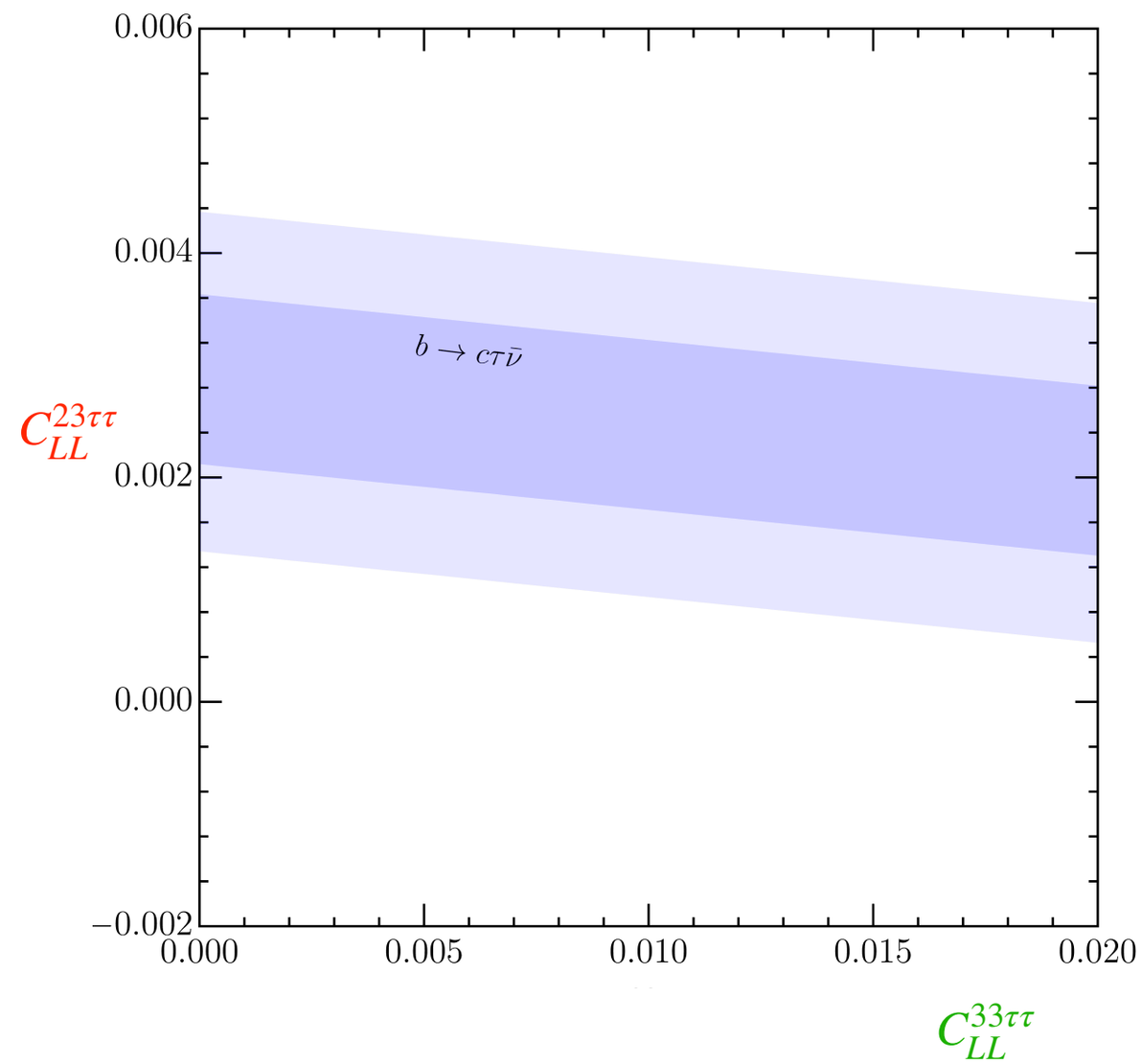

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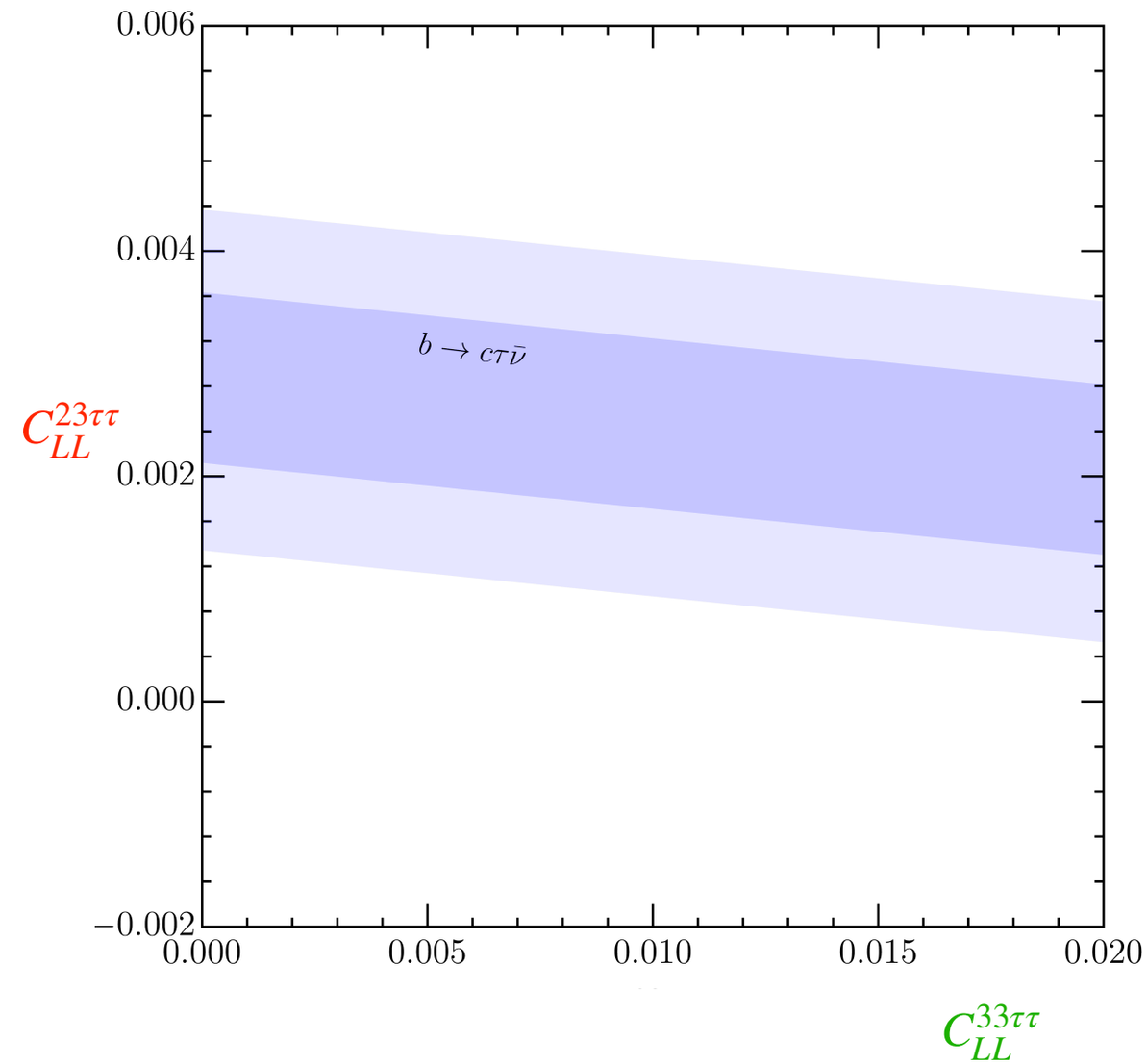

The very same couplings enter:

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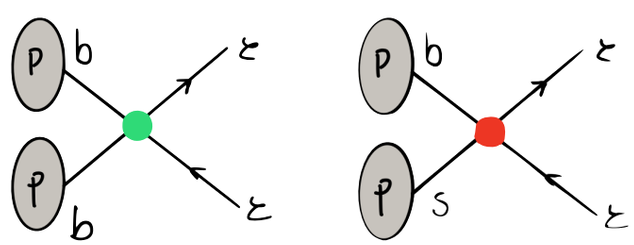

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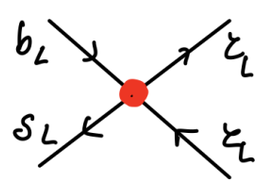
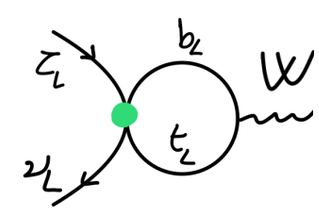


$W\tau\nu_\tau$



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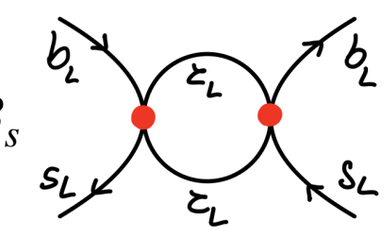

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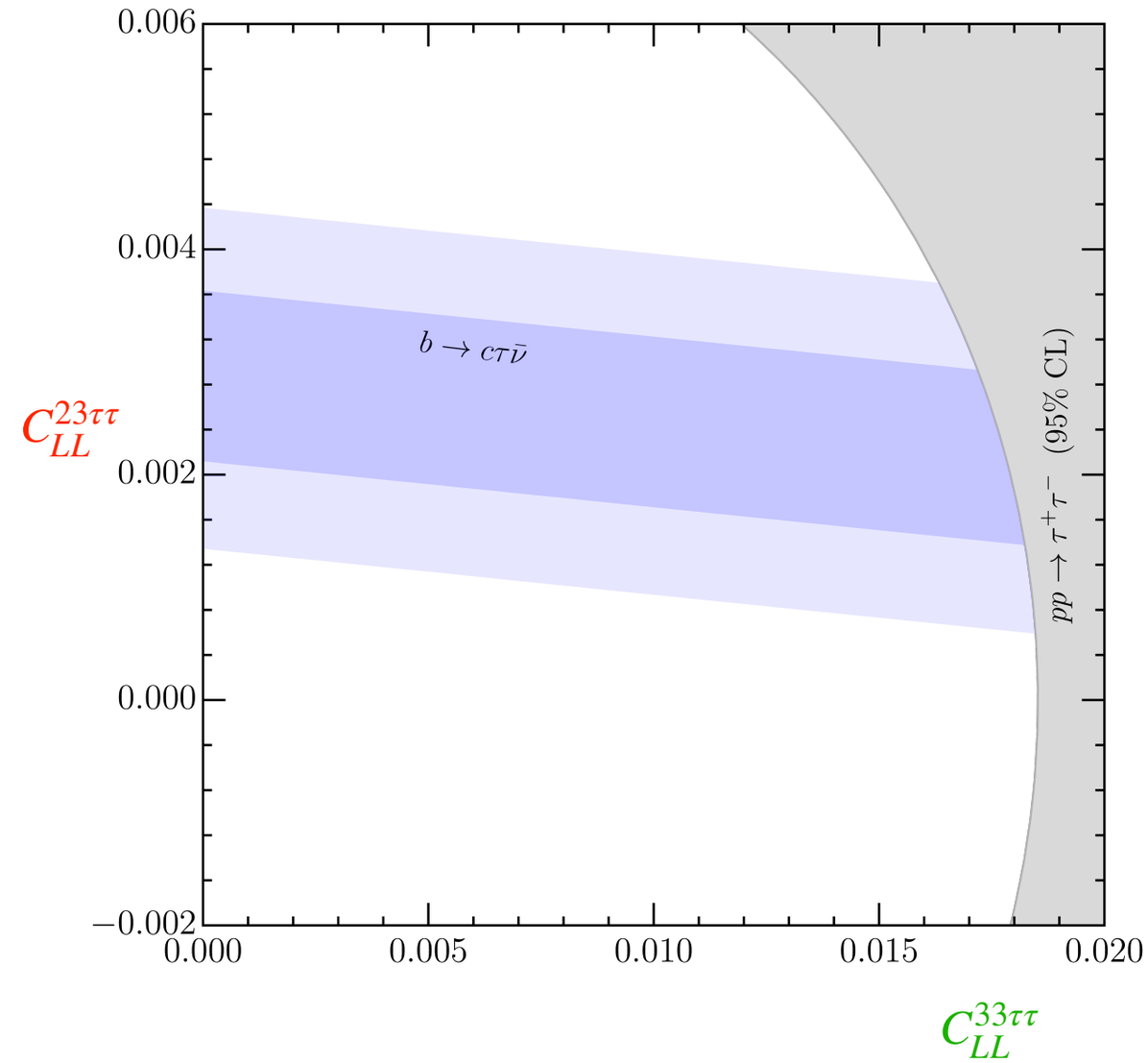

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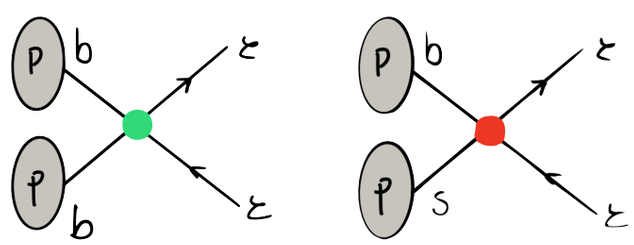

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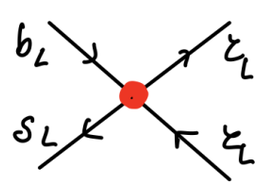

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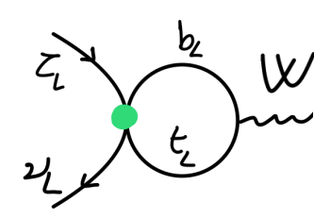

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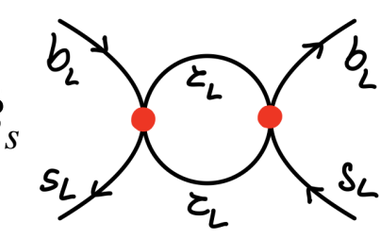

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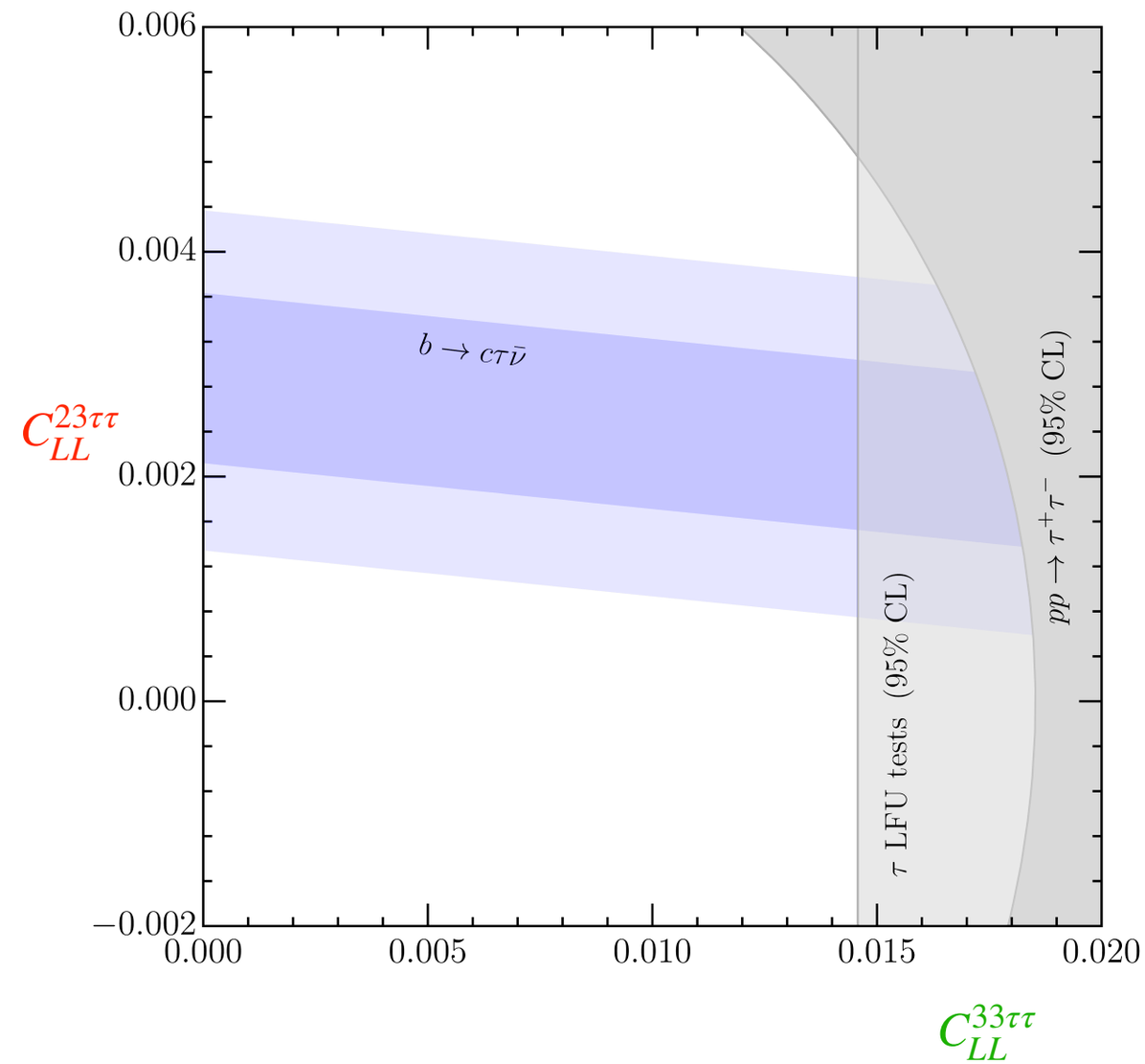

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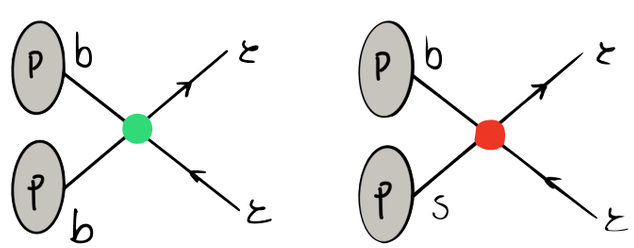

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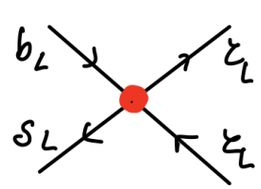

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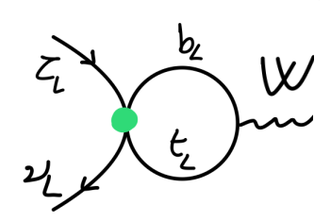

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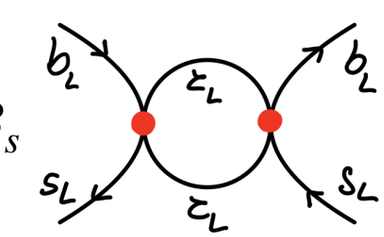

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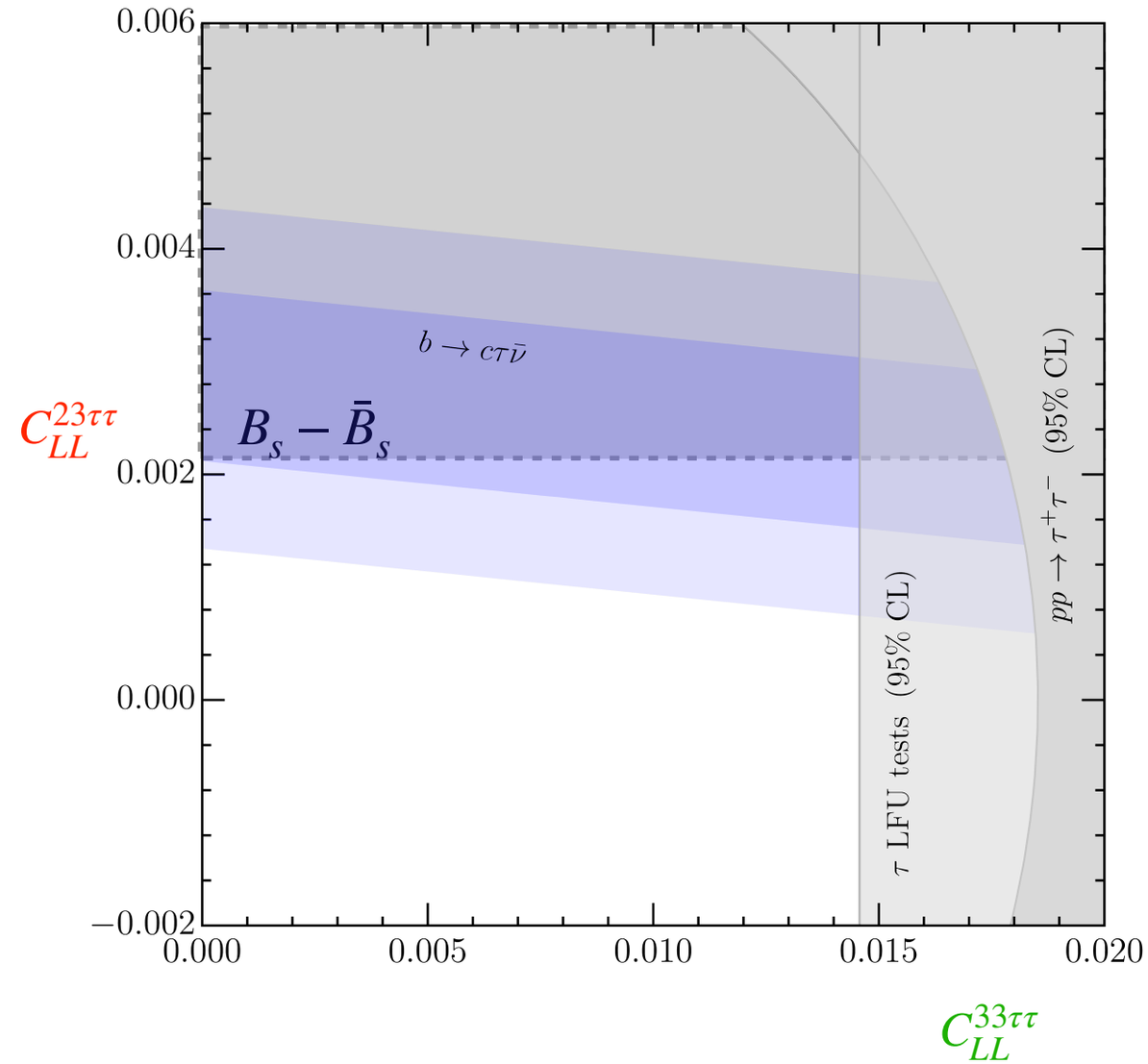

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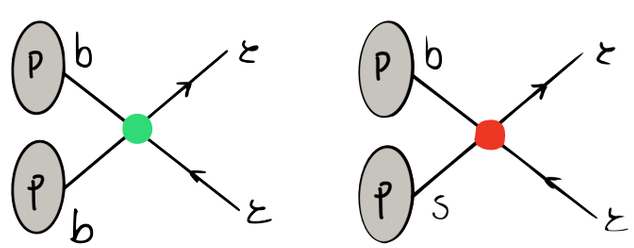

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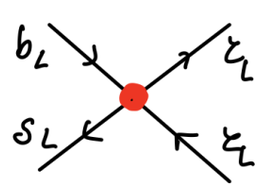

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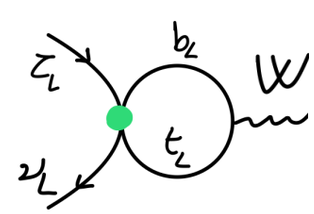

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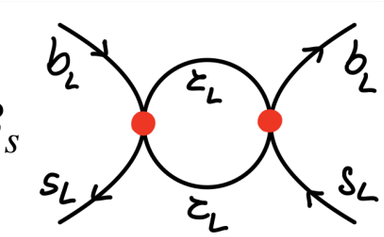

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- If NP couples only to LH fermions, $\delta R_{D^{(*)}}$ unavoidably implies per mil LFUV in τs:

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- If $\delta R_{D^{(*)}}$ is addressed only via scalar/tensor (e.g. R_2), no τ LFUV.

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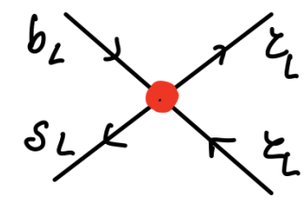
$$\Delta C_9^\tau = -\Delta C_{10}^\tau = -\frac{2\pi}{\alpha V_{ts}^* V_{tb}} C_{LL}^{23\tau\tau} \approx 40 \approx 10 \cdot C_{9,\mathrm{SM}}$$



$$\frac{\mathscr{B}(B_s \to \tau\tau)}{\mathscr{B}(B_s \to \tau\tau)_{\mathrm{SM}}} \approx \frac{\mathscr{B}(B \to K\tau\tau)}{\mathscr{B}(B \to K\tau\tau)_{\mathrm{SM}}} \approx \frac{|\Delta C_9^\tau|^2}{|C_{9,\mathrm{SM}}|^2} \approx 1 \cdot 10^2 \qquad \text{i.e. BR} \sim \text{few} \cdot 10^{-5}$$

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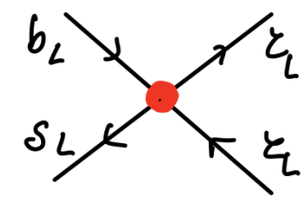
$$\Delta C_9^\tau = -\Delta C_{10}^\tau = -\frac{2\pi}{\alpha V_{ts}^* V_{tb}} C_{LL}^{23\tau\tau} \approx 40 \approx 10 \cdot C_{9,\mathrm{SM}}$$



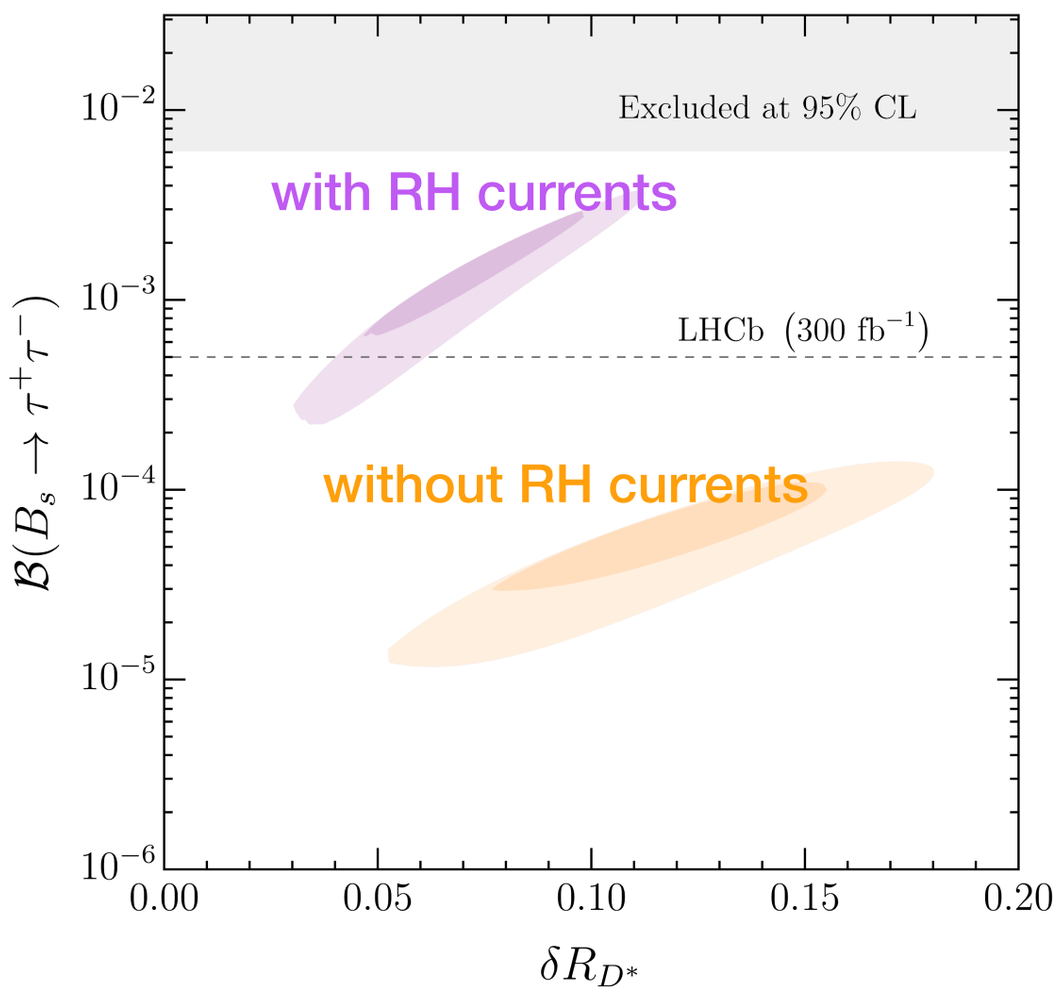
$$\frac{\mathscr{B}(B_s \to \tau\tau)}{\mathscr{B}(B_s \to \tau\tau)_{\mathrm{SM}}} \approx \frac{\mathscr{B}(B \to K\tau\tau)}{\mathscr{B}(B \to K\tau\tau)_{\mathrm{SM}}} \approx \frac{|\Delta C_9^\tau|^2}{|C_{9,\mathrm{SM}}|^2} \approx 1 \cdot 10^2 \quad \text{i.e. BR} \sim \text{few} \cdot 10^{-5}$$

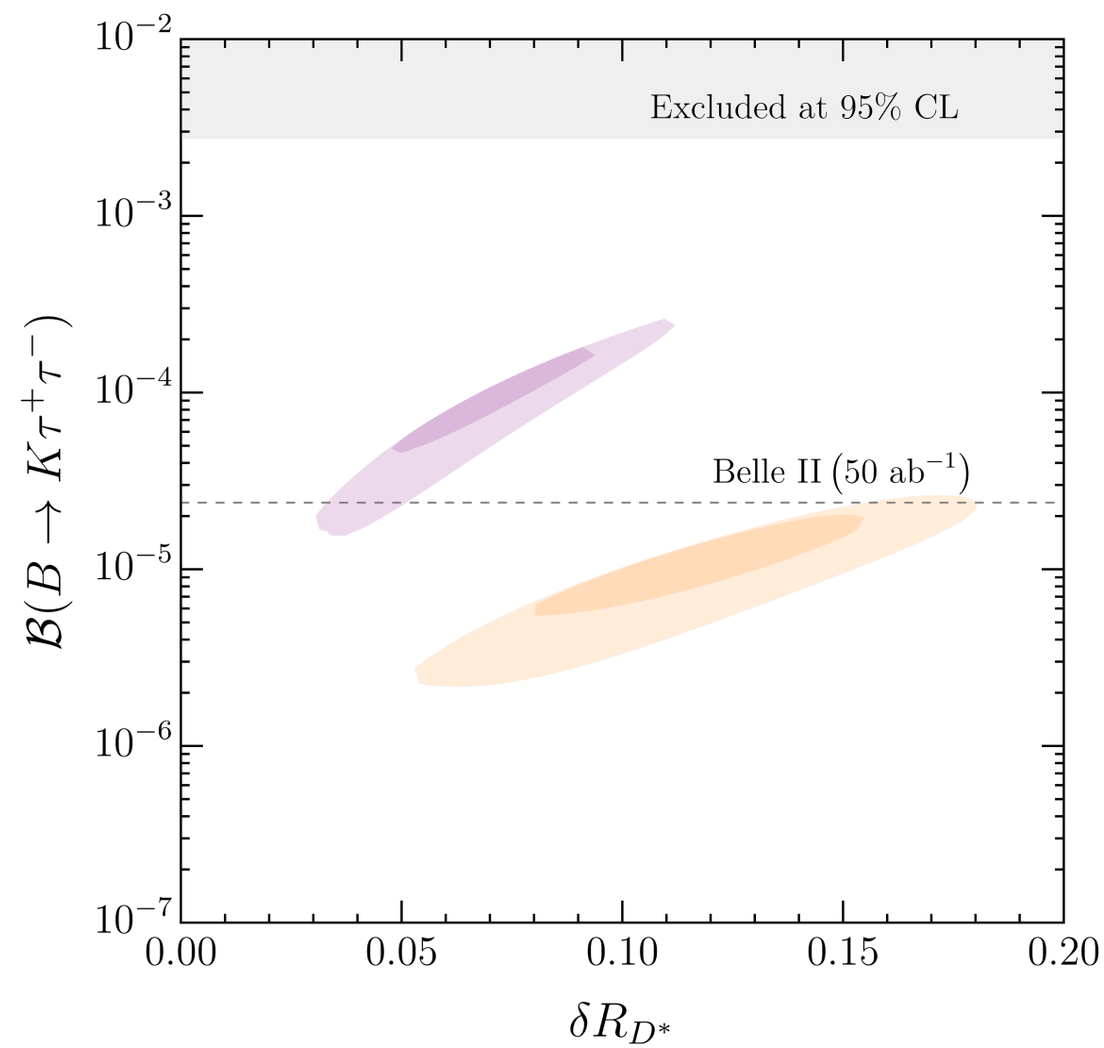
- with RH couplings one gets scalar/pseudo-scalar operators, whose contribution is chirally enhanced

E.g. U_1 coupled to LH & RH 3rd fam.

$$\frac{\mathscr{B}(B_s \to \tau\tau)}{\mathscr{B}(B_s \to \tau\tau)_{\mathrm{SM}}}, \frac{\mathscr{B}(B \to K\tau\tau)}{\mathscr{B}(B \to K\tau\tau)_{\mathrm{SM}}} \approx 1 - 2 \cdot 10^3 \quad \text{i.e.} \quad \text{BR} \sim \text{few} \cdot 10^{-4}$$

$b \to s\tau\tau$ at low energy for the U_1



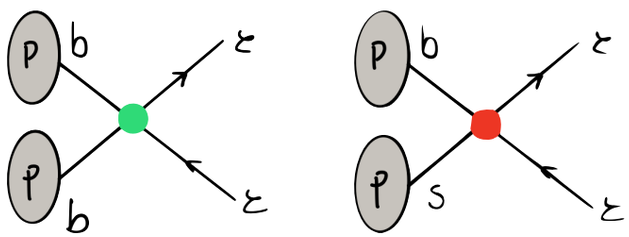


$bb(s) \to \tau\tau$ at high pT

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

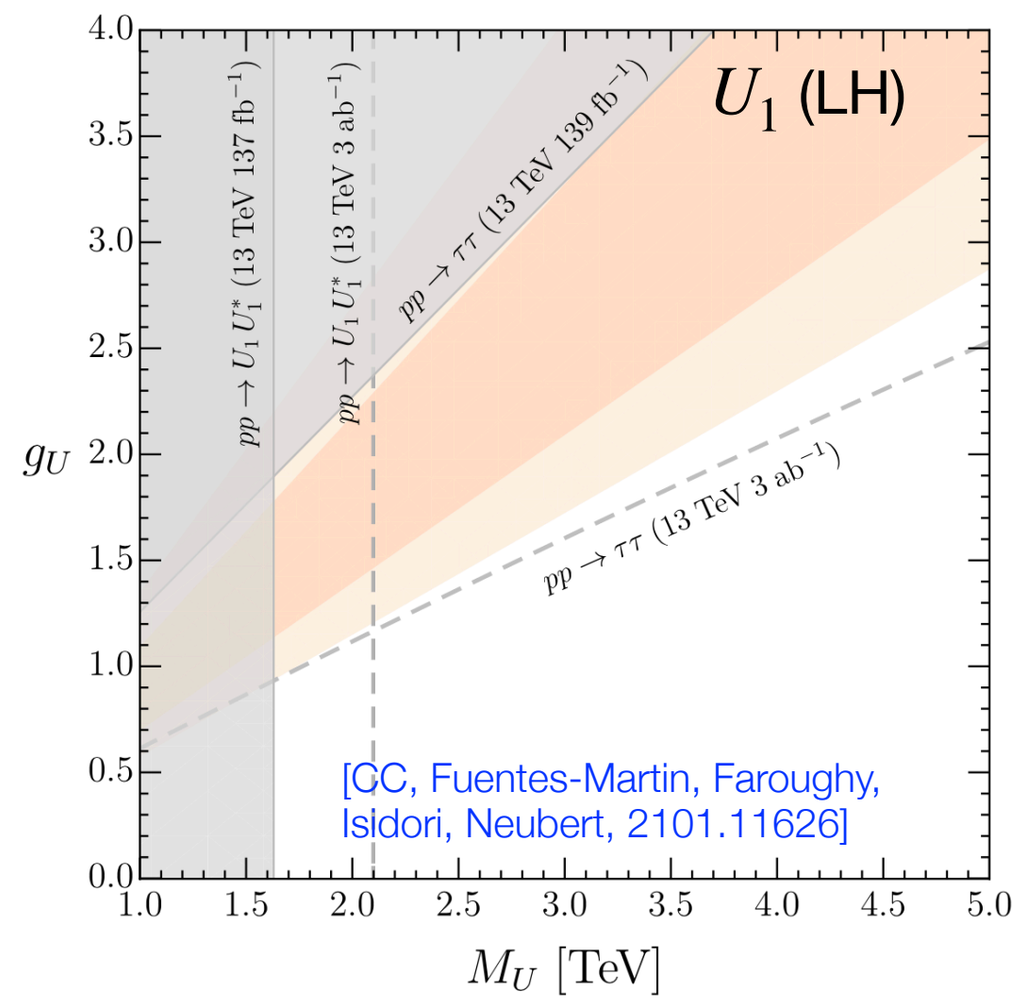
Generally **stronger** than low-E bounds!

$pp \to \tau\tau$



U_1 sol. will be completely probed at HL-LHC, same for $R_2 + S_3$, still space left for $S_1 + S_3$.

Models for $R_D^{(*)}$ only yield similar enhancements in $B \to K\tau\tau$, $B_s \to \tau\tau$ and $pp \to \tau\tau$.



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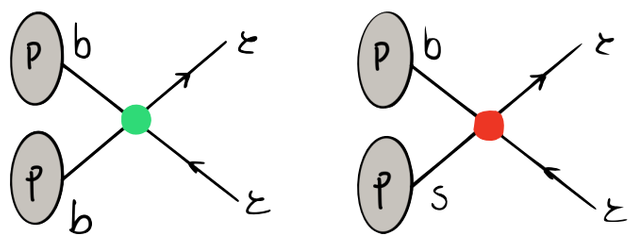

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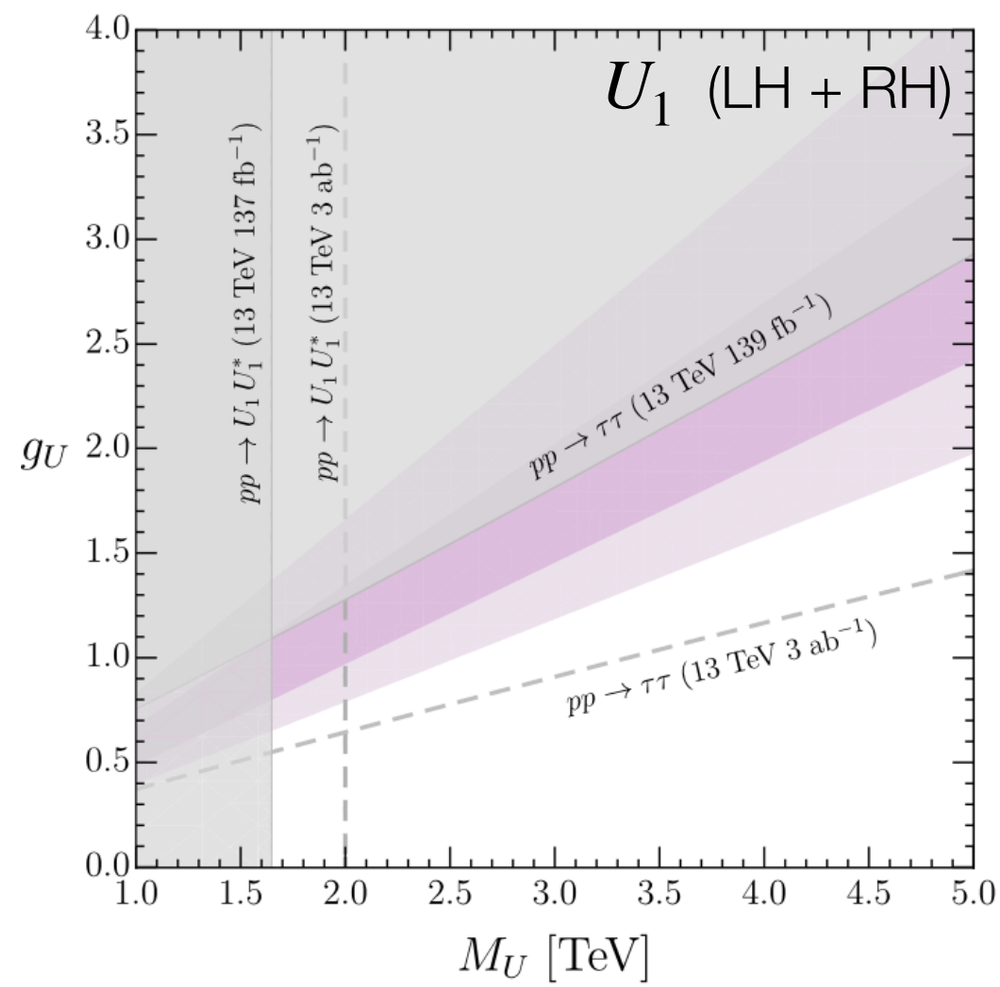

LFV in $b \to s\tau\mu$ and τ decays

$b \to sll$ **and** $b \to c\tau\nu$ $\longleftrightarrow$ τ/μ **LFV** in $b \to s\tau\mu$ and τ decays

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

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$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^{\mu} \beta_L^{i\alpha} (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) + {\rm h.c.}$$

$$\beta_L = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \beta_{s\mu} & \beta_{s\tau} \\ 0 & \beta_{b\mu} & \beta_{b\tau} \end{bmatrix}$$

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$\tau \to \mu\phi$

$\tau \to \mu\gamma$

$B_s \to \tau\mu\,, B \to K\tau\mu$

These predictions are subject to large uncertainties!
(B anomalies fix product of couplings, not individual coefficients…)

LFV in $b \to s\tau\mu$ and τ decays

- LH case

$$\mathscr{B}(B \to K\tau\mu) \approx \mathscr{B}(B_s \to \tau\mu) \approx 10^{-7} - 10^{-5}$$

$$\mathscr{B}(\tau \to \mu\phi) \approx 10^{-11} - 10^{-8}$$

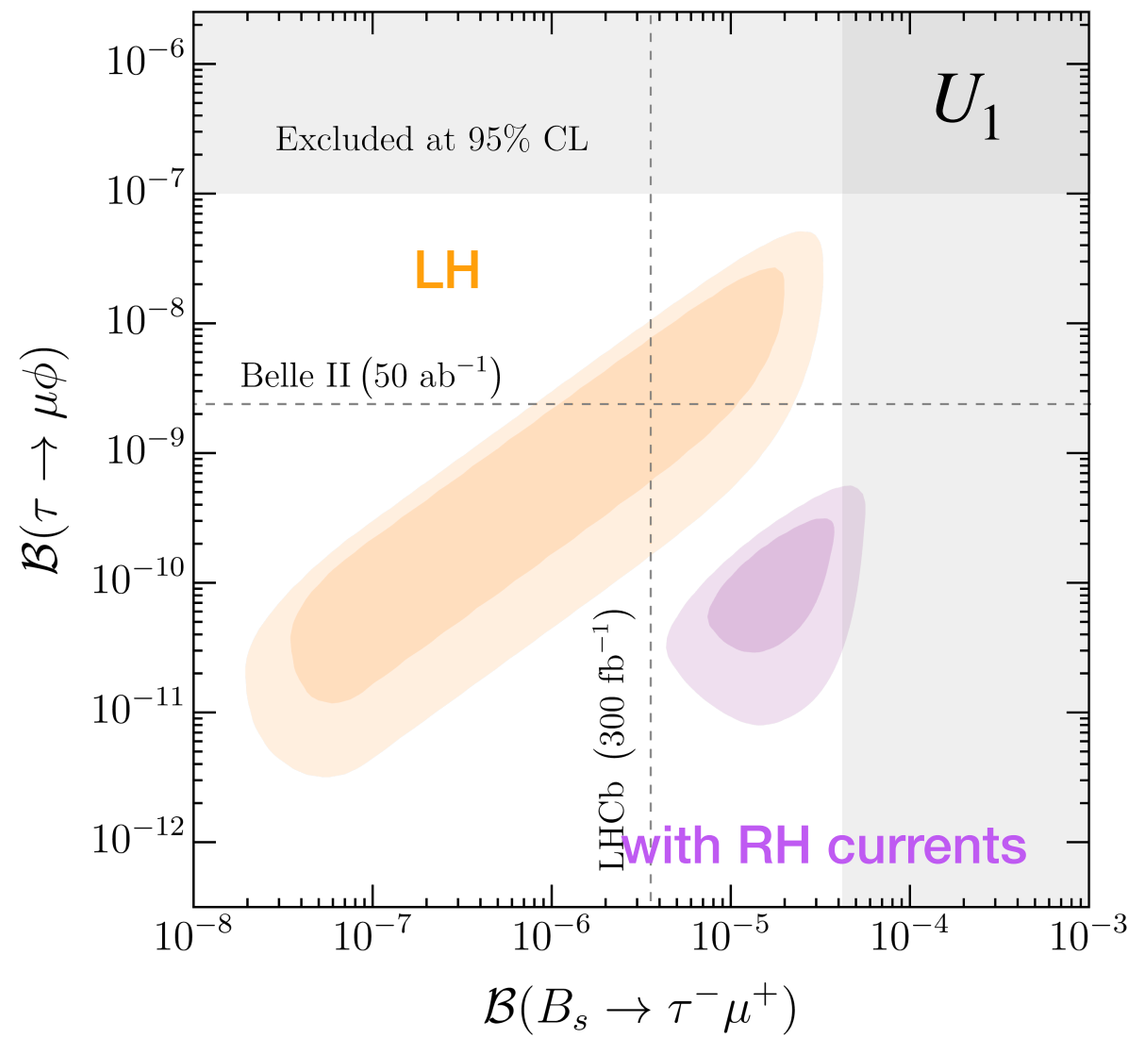
- With RH currents (U_1)

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

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

$$\mathscr{B}(\tau \to \mu\phi) \approx 10^{-11} - 10^{-10}$$

sensitive to the vector contribution only

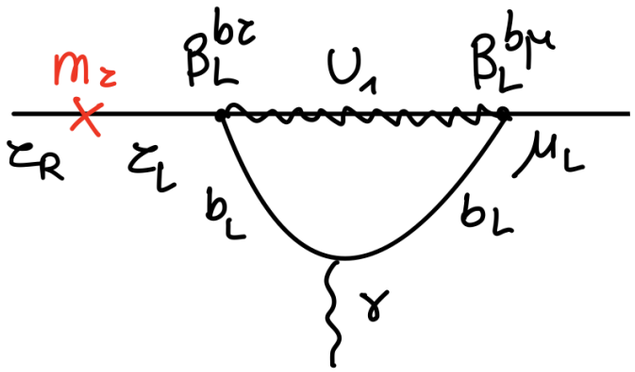


sensitive to (chirally enhanced) scalar contribution, hence larger than in the LH case

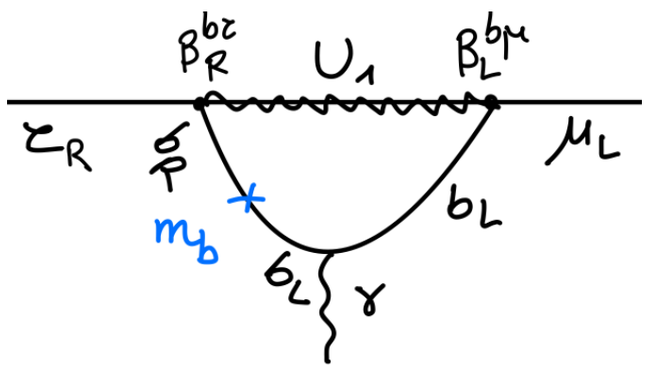
$\tau - \mu\gamma$

- NP couples only to LH fermions

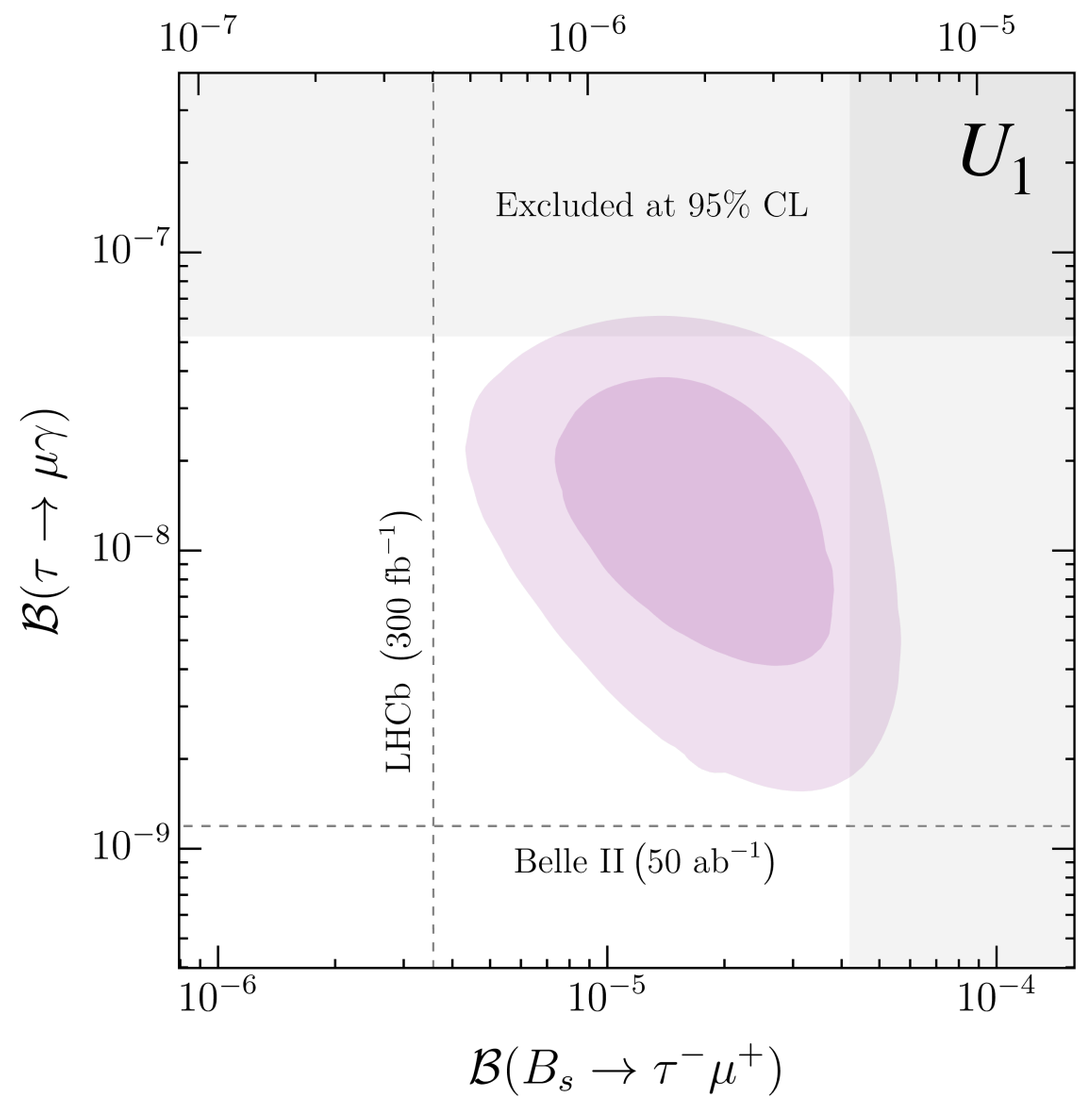
chiral suppression!



- RH couplings can lift it:



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



Conclusions

Present data in $b \to c$ imply large effects in many obs. at low and high energy, putting a fair amount of pressure on the parameter space of all* NP models for $R_{D^{(*)}}$.

No way out on the model building side: need experimental corroboration to guide us!

Obs. with τ leptons provide a strong consistency test of the $b \to c$ anomaly and help us characterize / rule out possible NP effects.

Ranked by constraining power:

- τ LFUV , $pp \to \tau\tau$
- τ/μ LFV in $b \to s\tau\mu$ and τ decays