Looking for New Physics in B decays at Belle II

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Introduction

A variety of BSM scenarios have interesting implications for B-physics.

Here I will focus on **BSM models for the B anomalies,**

$b \to s$ anomalies

μ vs e ~~universality~~ in $b \to sll$

+ ang. obs. and rates in $b \to s\mu\mu$

$\sim 4\,\sigma$

$b \to c$ anomalies

τ vs μ, e ~~universality~~ in $b \to cl\nu$

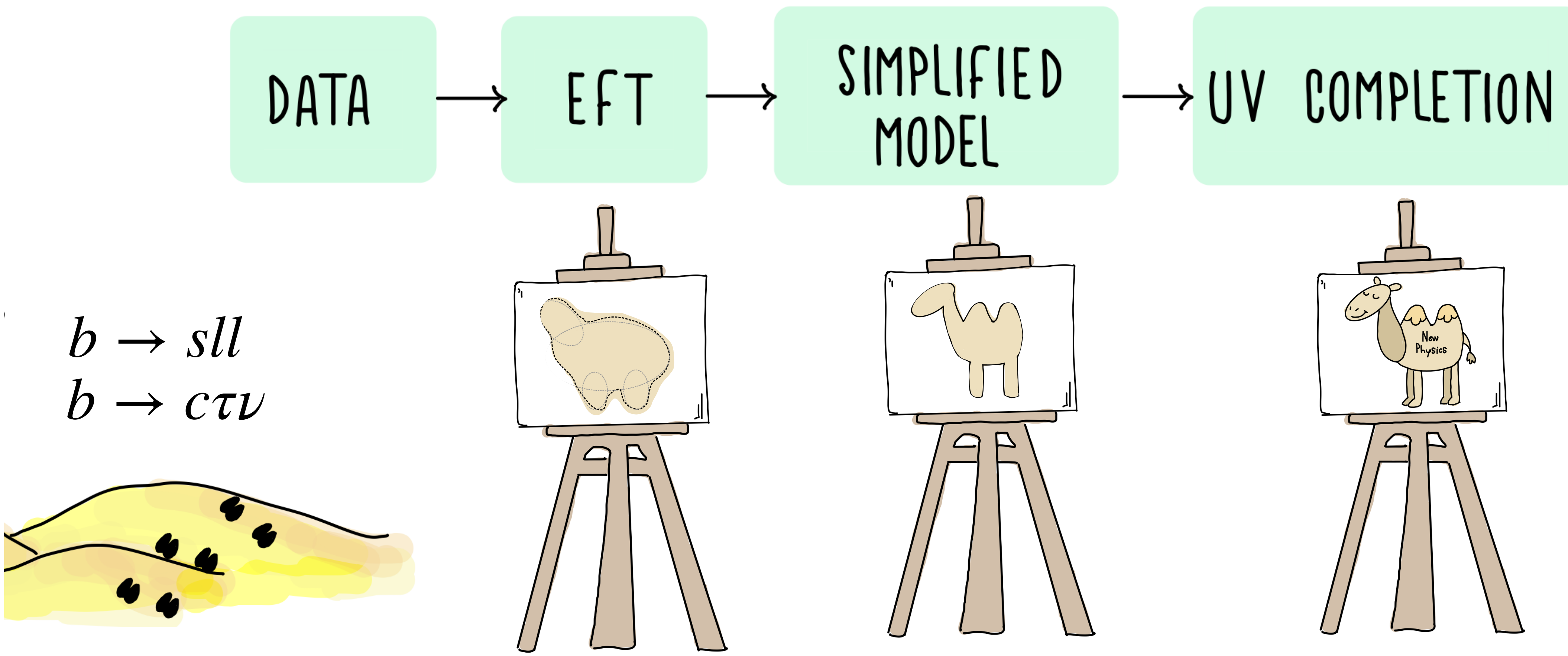
$\sim 3\,\sigma$

at present the only direct experimental motivation to expect NP in (other) B decays.

Reading the footprints of the B anomalies

? *If* the anomalies in $b \to sll$ and $b \to c\tau\nu$ are true NP signals, which NP could be responsible for them, and where else should we see it?

Usual strategy:



- at each step, we can investigate connections with other observables
- strength of connections becomes more model-dependent going from left to right)

EFT lessons

Minimal assumptions: B anomalies are real, and are due to some heavy NP.

Under these assumptions, the right framework to parametrize NP contributions to observables is an **Effective Theory**.

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The first place to look for similar effects are **observables in the same partonic transition** (ratios, BRs, angular distributions…):

$b \to s$ anomalies

- $B \to X_s \mu\mu$
- $B_s \to \mu\mu$
- $R_{pK}^{\mu/e}$

$b \to c$ anomalies

- Ang. dist. of $B \to D^{(*)}\tau\nu$
- $F_L(D^*)$, $P_\tau(D^*)$
- $R_{D^+}, R_{D^*}, R_{D^{**}}, R_{D_s^*}, R_{\Lambda_c} \ldots$

On top of assessing the "**size**" (scale) of the NP effect, these observables help us pin down its Lorentz structure.

Observables in $b \to c\tau\nu$

$$\mathscr{L}_{\rm eff} = -2\sqrt{2}G_F V_{cb}\Big[(1+g_{V_L})(\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L)+g_{V_R}(\bar{c}_R\gamma^\mu b_R)(\bar{\tau}_L\gamma_\mu\nu_L)+g_{S_R}(\bar{c}_L b_R)(\bar{\tau}_R\nu_L) + g_{S_L}(\bar{c}_R b_L)(\bar{\tau}_R\nu_L)+g_T(\bar{c}_R\sigma^{\mu\nu}b_L)(\bar{\tau}_R\sigma_{\mu\nu}\nu_L)\Big]$$

Switching on only one WC at a time, only g_{V_L} is able to account for all $b \to c$ data.
But different solutions, e.g. $V_L + S_R, S_L + T\ldots$ are still possible.

Looking at different obs. in $b \to c\tau\nu$ can help us disentangle these scenarios.

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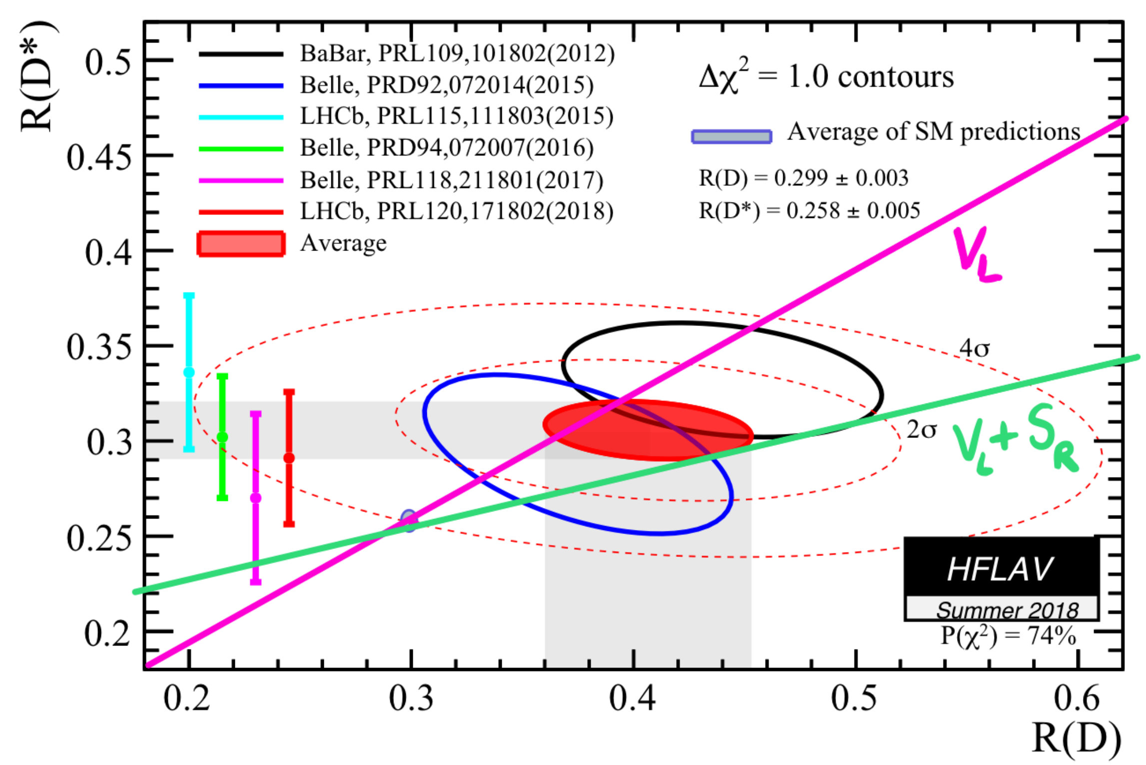
LFU ratios

V_L only $\quad \Delta R_D = \Delta R_D^*$

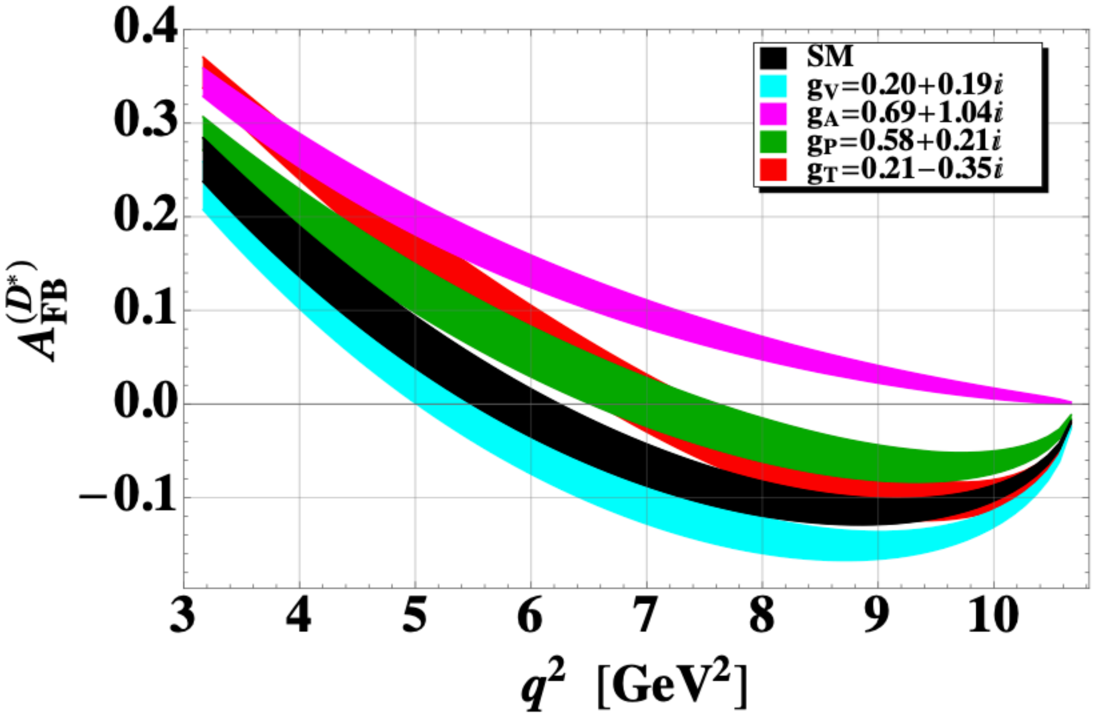
$V_L + S_R \quad \Delta R_D > \Delta R_{D^*}$

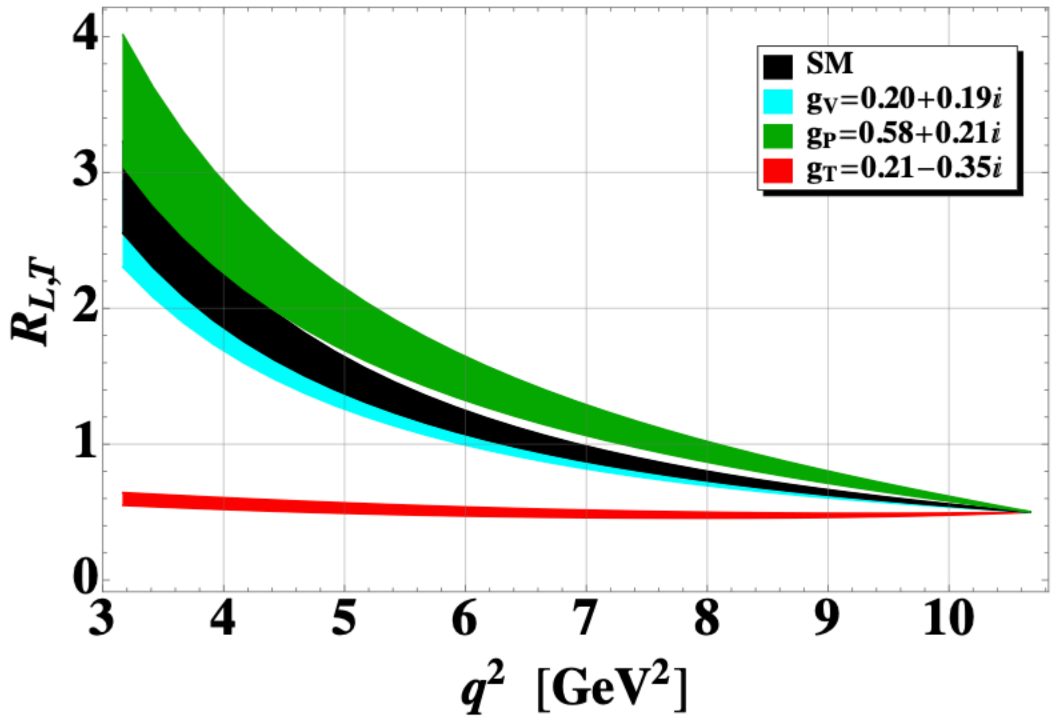
$$\Delta R_i \equiv \frac{R_i}{R_i^{\rm SM}} - 1$$



Observables in $b \to c\tau\nu$

Ang. observables, polarizations…





See also Murgui et. al (2019) for a similar analysis

More precise measurements of ratios, angular correlations, polarizations, and asymmetries are crucial to disentangle these scenarios.

Many of these are more easily accessible at Belle II w.r.t. LHCb.

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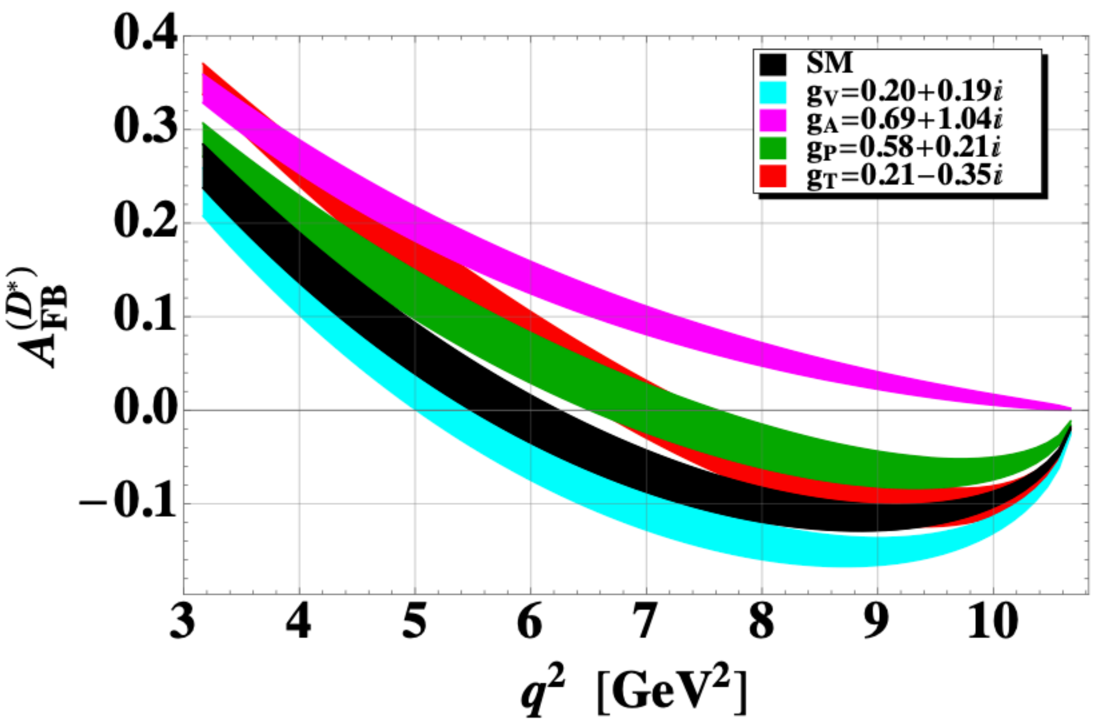
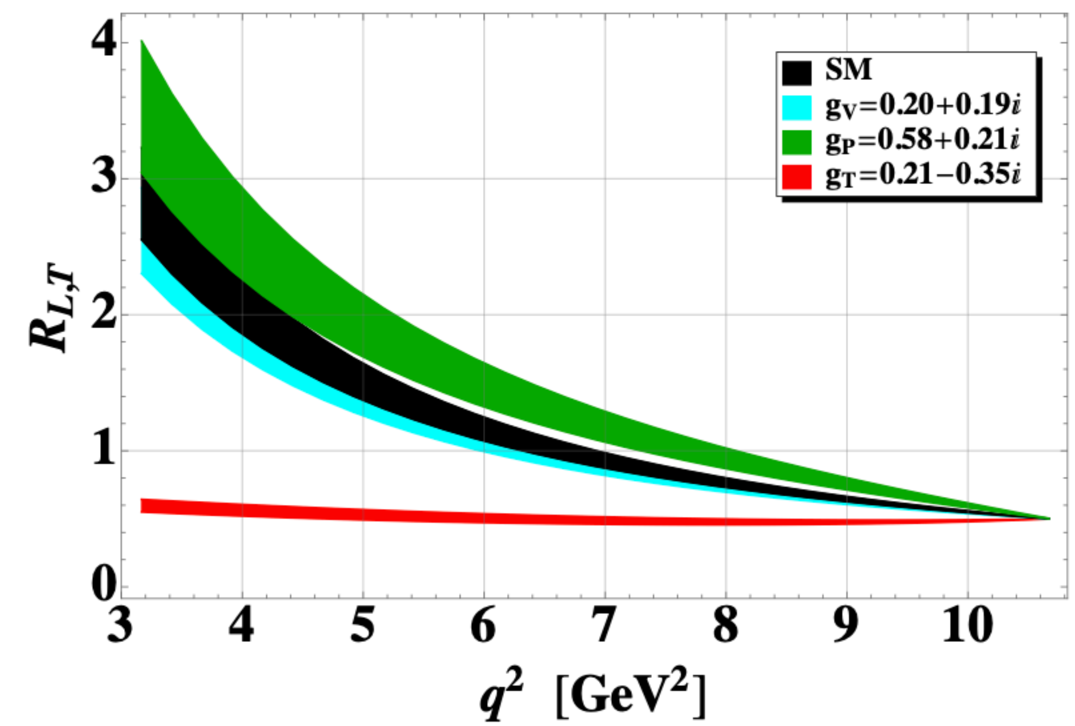
[Becirevic et al. (2019)]





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Combined explanation of the B anomalies

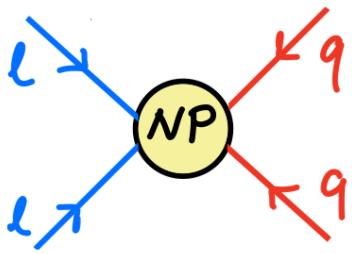
The two anomalies fit well in the SMEFT:

$$b \to sll \qquad\qquad b \to cl\nu$$

$$(\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L) \quad \xleftrightarrow{SU(2)_L} \quad (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L)$$

⇒ Minimal solution: **left-handed, TeV scale NP in semi-leptonic operators**:

$$\mathscr{L}_{\rm EFT}^{\rm NP} = -\frac{1}{v^2}\Big(C_{lq}^{(3)}(\bar{l}_L \gamma^\mu \tau^a l_L)\big(\bar{q}_L \gamma^\mu \tau^a q_L\big) + C_{lq}^{(1)}\left(\bar{l}_L \gamma^\mu l_L)(\bar{q}_L \gamma^\mu q_L\right)\Big) + \ldots$$



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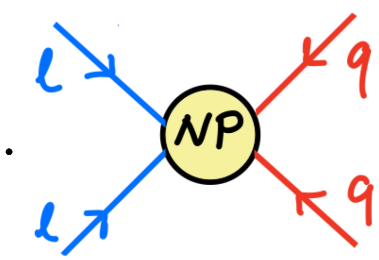


The only viable tree-level mediators are **leptoquarks**:
no 4ℓ and 4q processes at tree level, and no resonant production at LHC.

Three possibilities (for a combined explanation):

$S_1 + S_3$ [Crivellin et al. (2017); Buttazzo et al. (2017); Marzocca (2018)...]

$S_3 + R_2$ [Bečirević et al. (2018 ,2022)

U_1 [di Luzio et al. (2017); Calibbi et al. (2017); Bordone, CC, et al. (2017); Barbieri, Tesi (2017); Heck,Teresi (2018)...]

General phenomenological consequences

1. **Large** $b \to s\tau\tau$

2. **Large** τ/μ **violation in B and** τ **decays**

3. **Enhancement of** $B \to K\nu\bar{\nu}$

Belle II plays an important role in assessing all these effects.

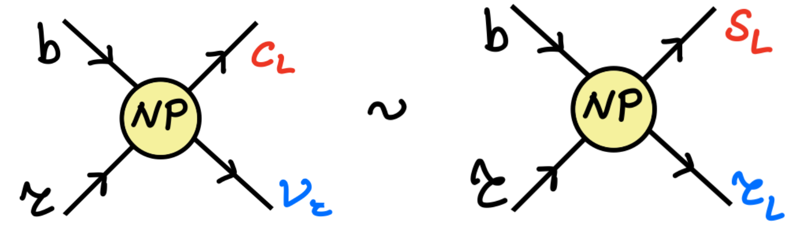
Large $b \to s\tau\tau$

[(*)Exception: R2 + S3]

Driven by the CC anomaly (when explained via the triplet(*))

$$\ell_L^3 = \begin{bmatrix} \nu_\tau \\ \tau_L \end{bmatrix} \quad q_L^2 = \begin{bmatrix} c_L \\ s_L \end{bmatrix}$$

$SU(2)_L$ invariance $\Rightarrow$



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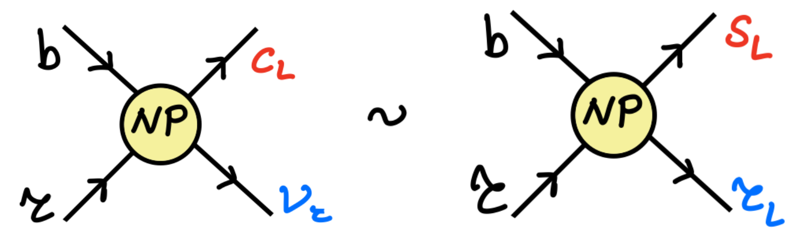

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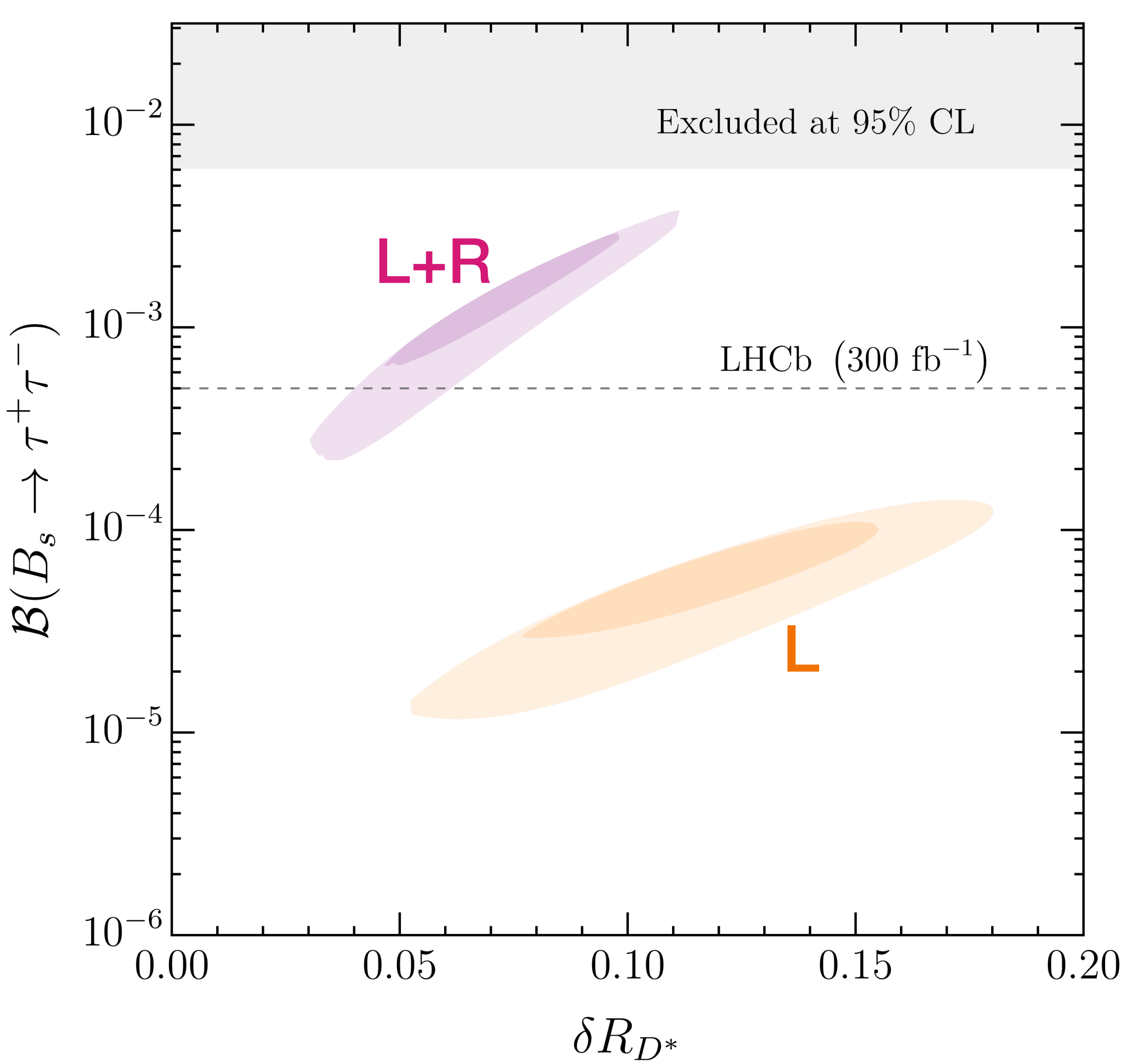
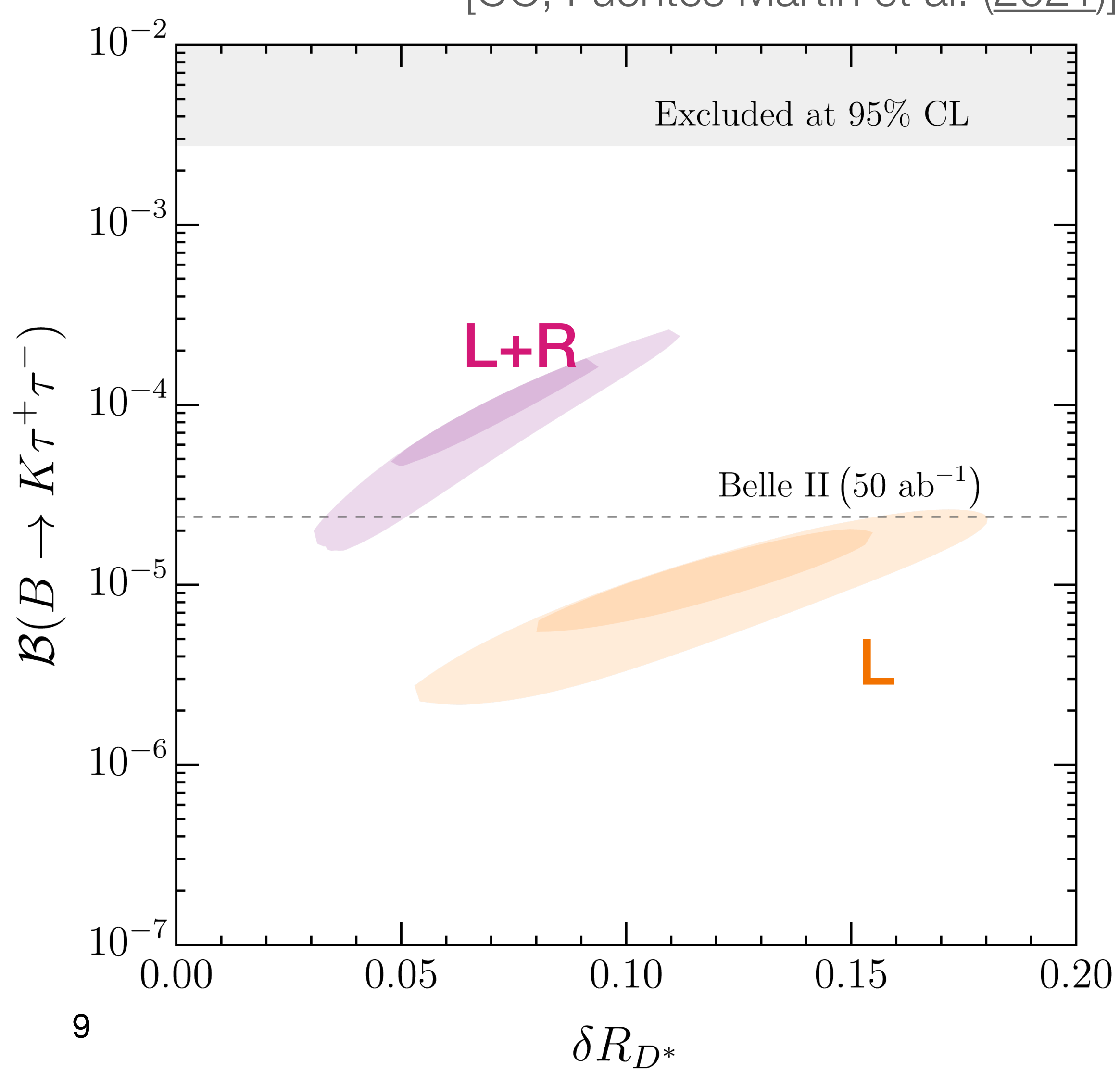
Projections for the U_1:

[CC, Fuentes Martin et al. (2021)]





High-pT bounds from $pp \to \tau\tau$

[Faroughy, Greljio, Kamenik (2016);
Fuentes-Martin et al. (2020)]

The same interaction can be probed in **di-tau tails** at the LHC.
The obtained bounds are generally stronger than the low-energy ones.

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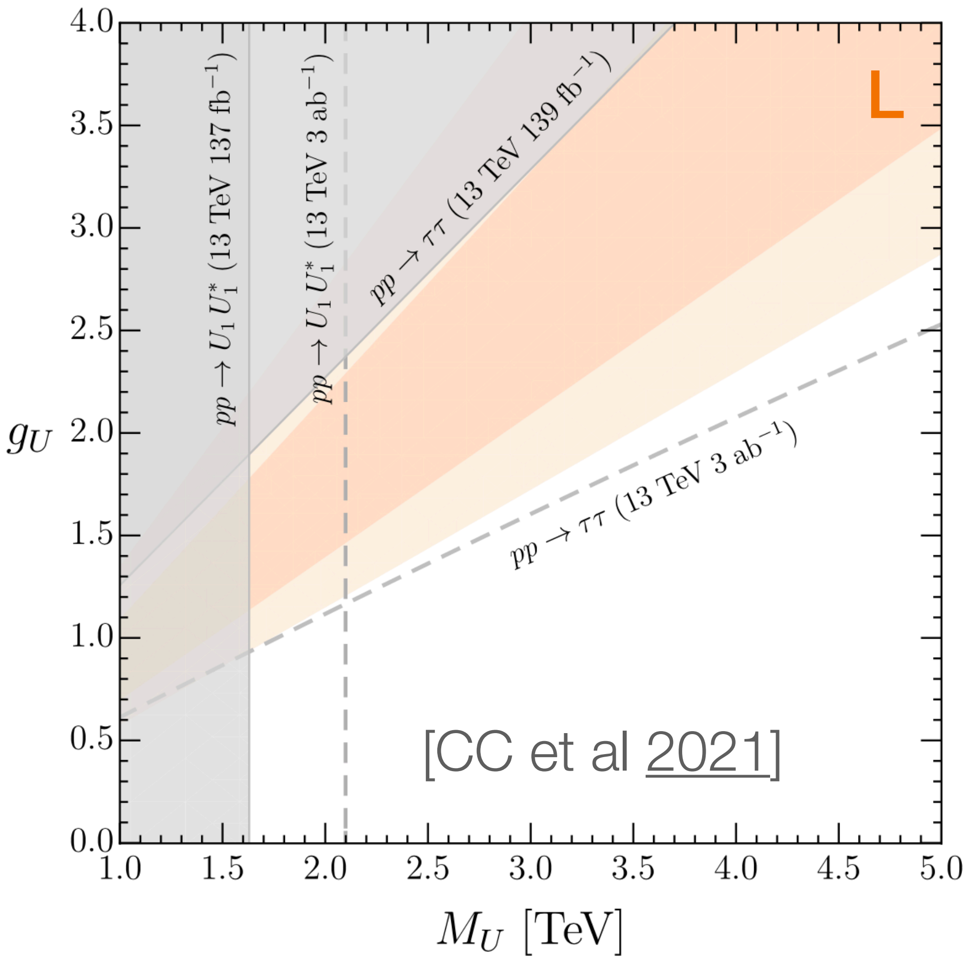
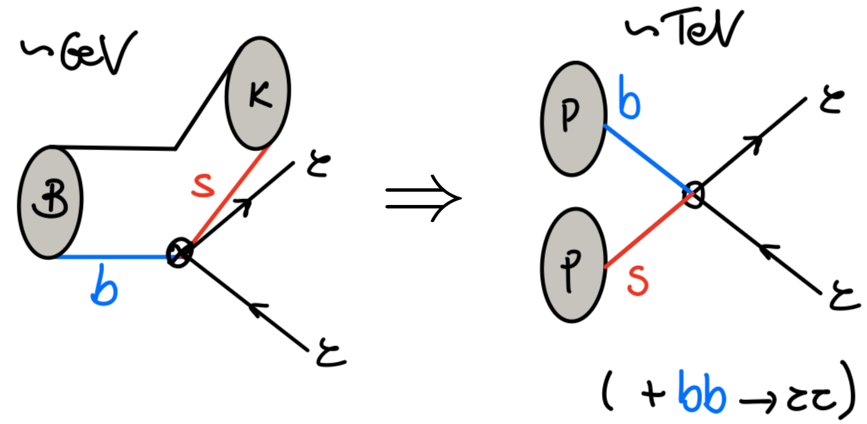


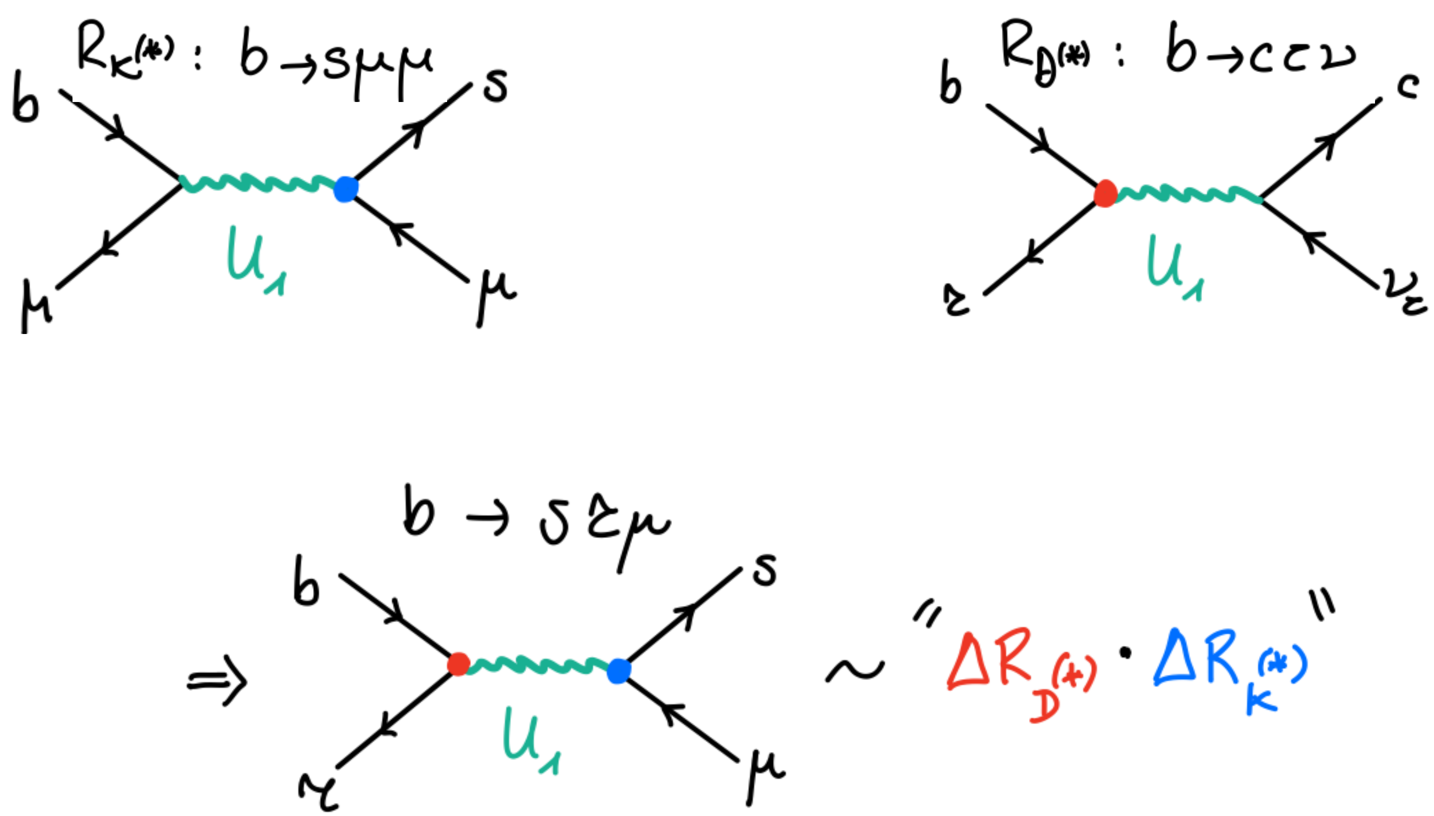


- U_1 solution is completely falsifiable at HL-LHC (or we will find a U_1!)
- same for $R_2 + S_3$,
- still space left for $S_1 + S_3$

Models for $R_D^{(*)}$ only yield similar enhancements in $B \to K\tau\tau$,$B_s \to \tau\tau$ and $pp \to \tau\tau$.
Any change in $R_D^{(*)}$ will alter these conclusions significantly.

Lepton Flavour Violation in $b \to s\tau\mu$ and τ decays

Driven by the presence of both CC and NC anomaly:



Lepton Flavour Violation in $b \to s\tau\mu$ and τ decays

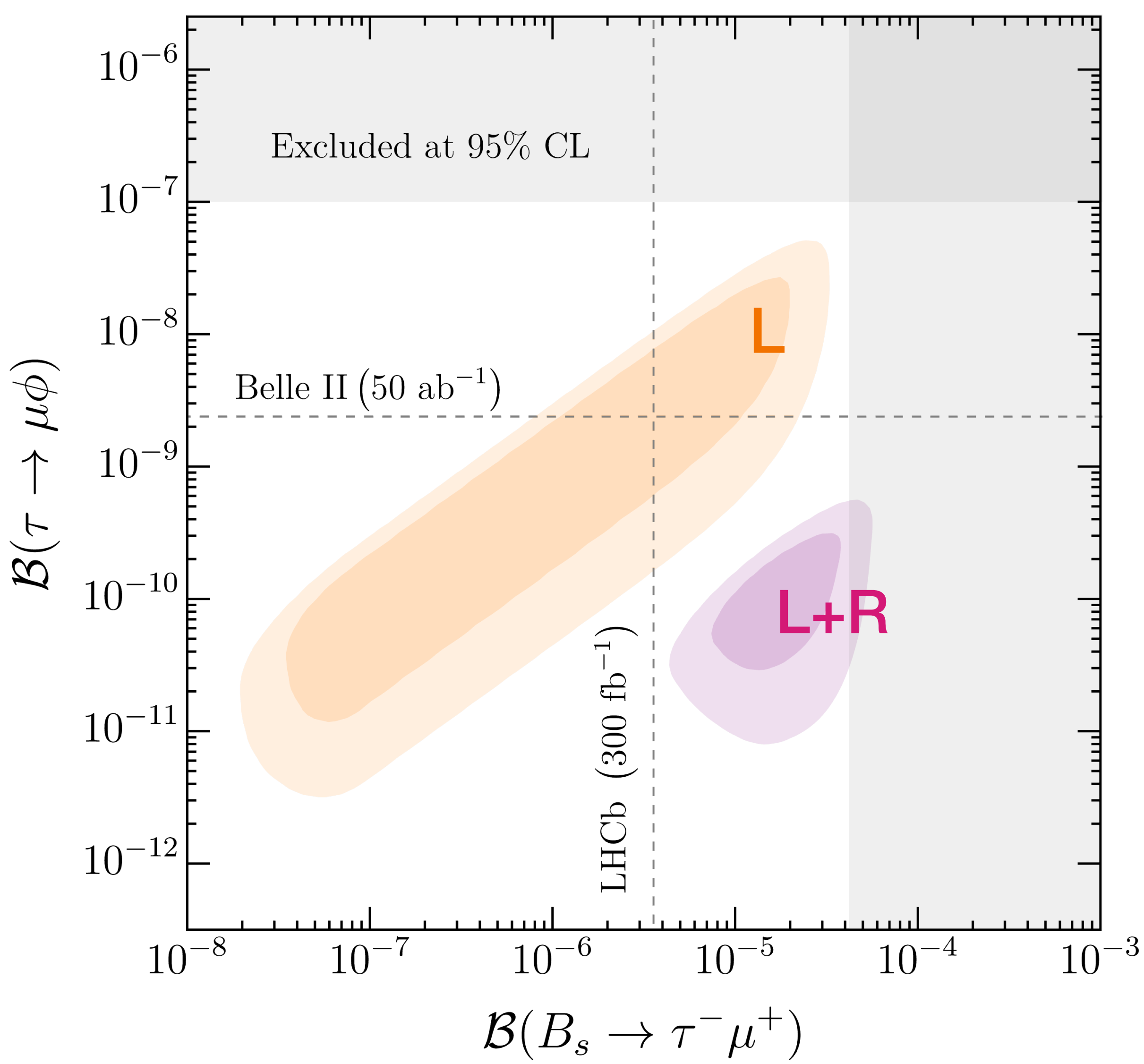
$$\mathcal{B}(B_s \to \tau\mu) \approx \mathcal{B}(B \to K\tau\mu) \approx 10^{-7} - 10^{-6}$$

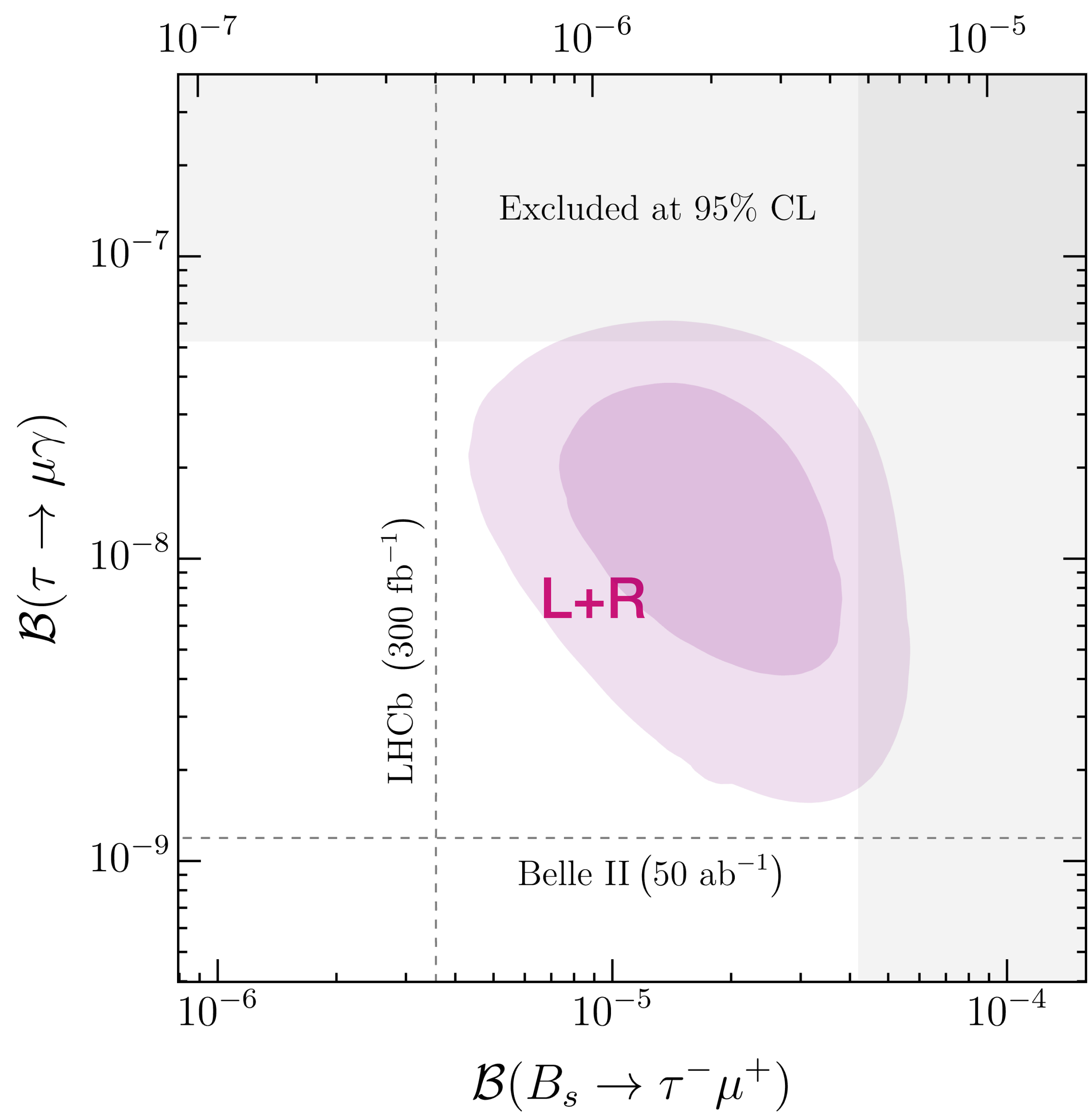
$$\mathcal{B}(\tau \to \mu\phi) \approx 10^{-10} - 10^{-8}$$

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

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

$$\mathcal{B}(\tau \to \mu\gamma) \approx 1 \times 10^{-8}$$





[CC, Fuentes Martin, Faroughty Isidori, Neubert, 2021]

Enhancement of $B \to K\nu\nu$

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$$\mathscr{A}(b \to s\nu\bar{\nu}) \propto \left(C_{lq}^{(3)} - C_{lq}^{(1)}\right)_{2333} \quad \Rightarrow$$

does $R_{D^{(*)}}$ ($\to$ large)

need $C_{lq}^{(3)} \approx C_{lq}^{(1)}$ at 1% level not to overshoot present bounds!

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→ **Belle II will probe the parameter space preferred by all these models entirely.**

Usual caveat: the size of the effect is driven by the CC anomaly.

Other interesting tests: $b \to d$ and $b \to u$

Belle II has the potential to test LFU in other quark transitions, like $b \to u$ and $b \to d$.

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Universality tests in $B \to \pi$:

$$\frac{\mathcal{B}(B \to \pi\tau\nu)}{\mathcal{B}(B \to \pi\ell\nu)} \approx \left.\frac{\mathcal{B}(B \to \pi\tau\nu)}{\mathcal{B}(B \to \pi\ell\nu)}\right|_{\rm SM} \left(0.75\,\frac{R_D}{R_D^{\rm SM}} + 0.25\,\frac{R_{D^*}}{R_{D^*}^{\rm SM}}\right)$$

$$\frac{\mathcal{B}(B \to \pi\mu\mu)}{\mathcal{B}(B \to \pi ee)} \approx R_{K^{(*)}}$$

Conclusions

BSM models for B anomalies predict a variety of signatures relevant for Belle II:

- Modifications of obs. In $b \to sll$ and $b \to c\tau\nu$
- Enhancement of $B \to K\tau\tau$
- $B \to K\tau\mu, \tau \to \mu\phi, \tau \to \mu\gamma$
- Enhancement of $B \to K\nu\bar{\nu}$
- Possibly effects in $b \to u$ and $b \to d$ transitions