Scalar leptoquarks for $R_{D^{(*)}}$

(and for $B \to K\nu\nu$)

EPS-HEP 2025

UNIVERZA V LJUBLJANI | FMF Fakulteta za matematiko in fiziko

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Ljubljana, Slovenia

(based on 2404.16772 and 2410.23257 with D. Bečirević, S. Fajfer and N. Košnik)

Lovre Pavičić 9.7.2025

Motivation

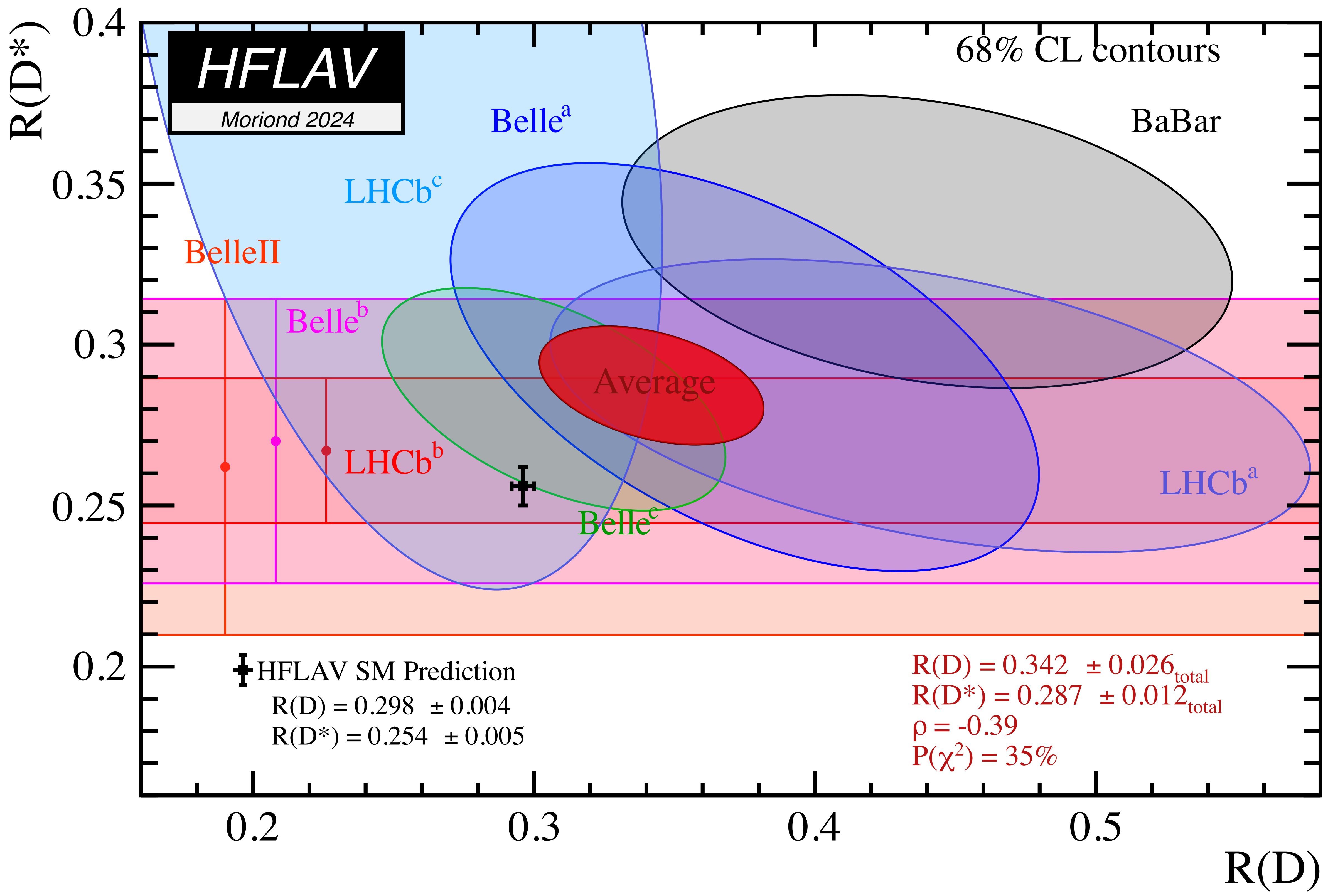
$$R_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)}, \quad \ell = e, \mu$$

- Lepton flavour universality

  $\Rightarrow$ Strong test of the Standard Model

- Theoretically clean; **hadronic uncertainties cancel** in the ratio

- SM predictions significantly smaller than experiment, **combined deviation:** $\sim 3.2\,\sigma$



$\Rightarrow$ Violation of LFU? **New Physics** coupled to b and τ?

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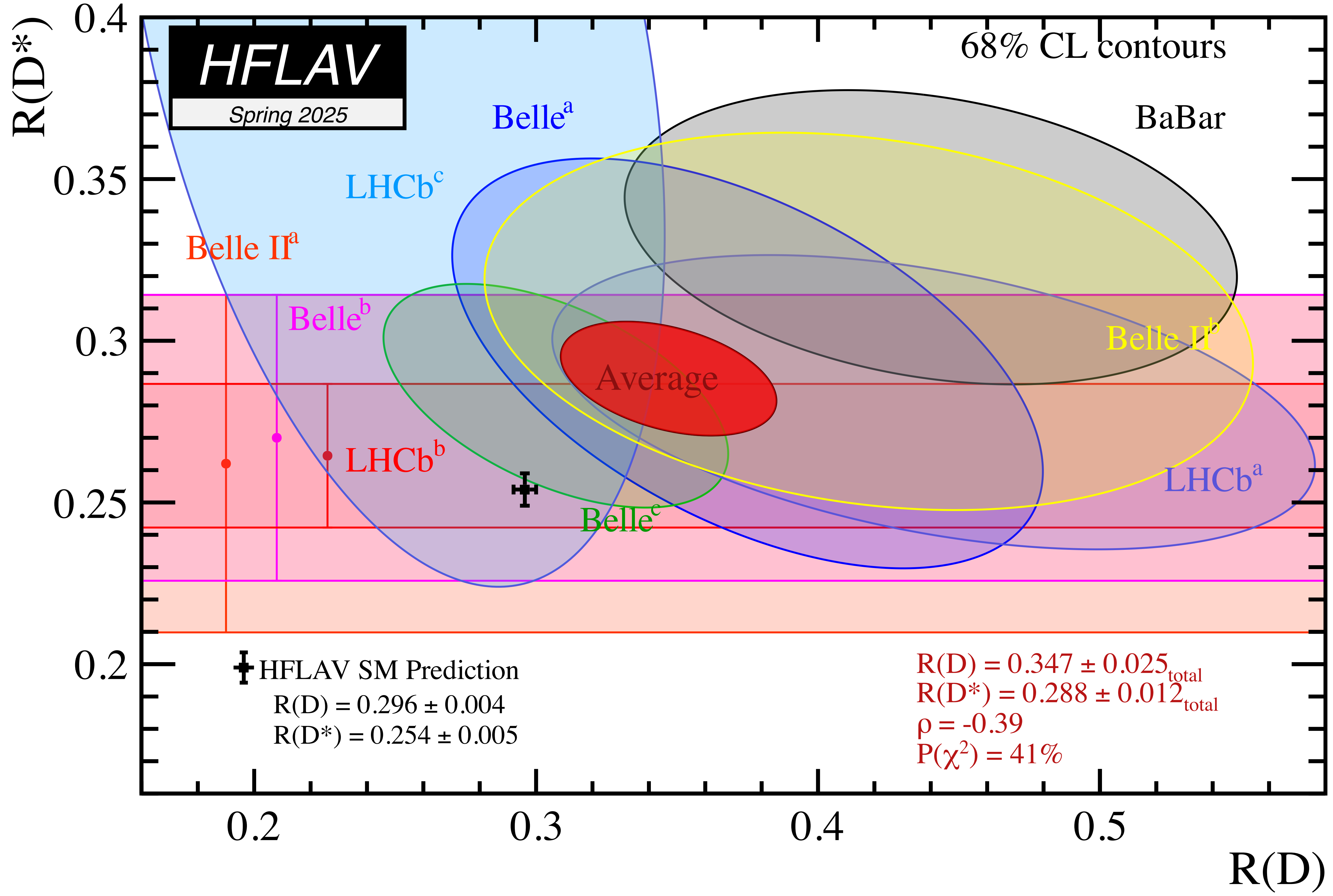

$\Rightarrow$ Violation of LFU? **New Physics** coupled to b and τ?

Possible explanations

$$\mathcal{L}_{b\to c\tau\nu} = -2\sqrt{2}G_F V_{cb}\Big[(1+g_{V_L})(\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_{\tau L}) + g_{V_R}(\bar{c}_R\gamma^\mu b_R)(\bar{\tau}_L\gamma_\mu\nu_{\tau L})$$
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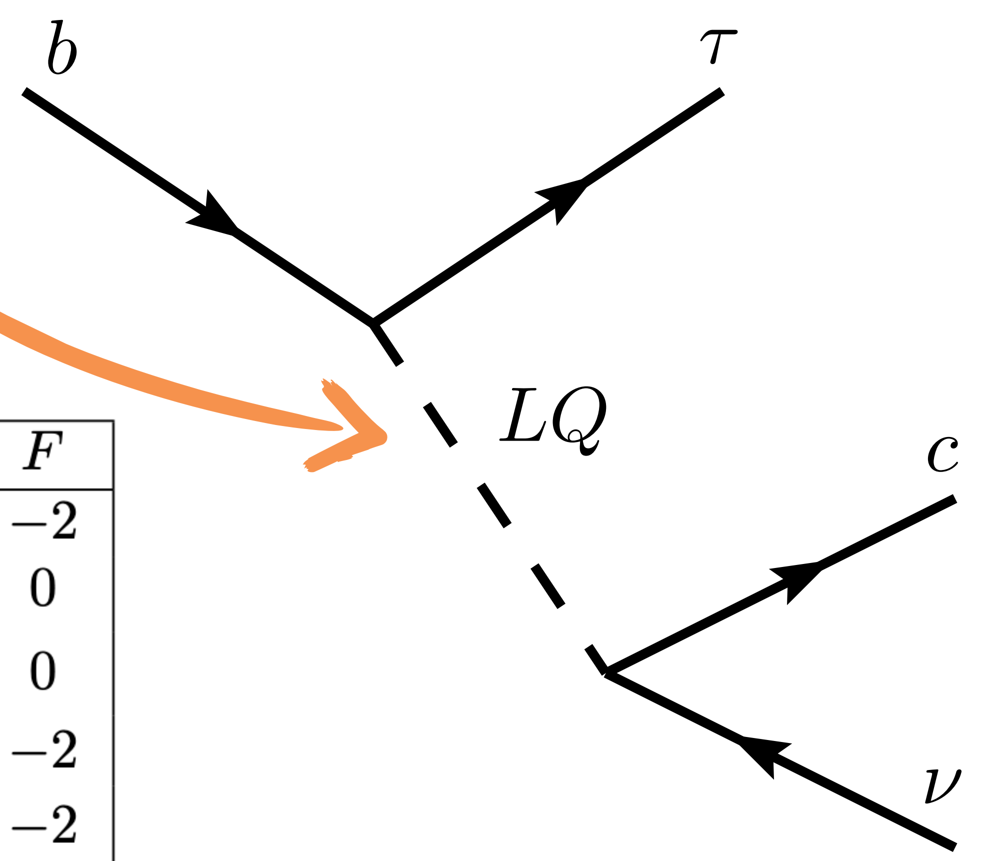
EFT study - $\Lambda_{NP} \simeq m_{NP}/C_{NP} \sim \mathcal{O}(1-3)\mathrm{TeV}$

- Possible NP solutions: W', Charged Higgses, Exotic neutrino interactions...



- **Or Leptoquarks!**

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(1603.04993)

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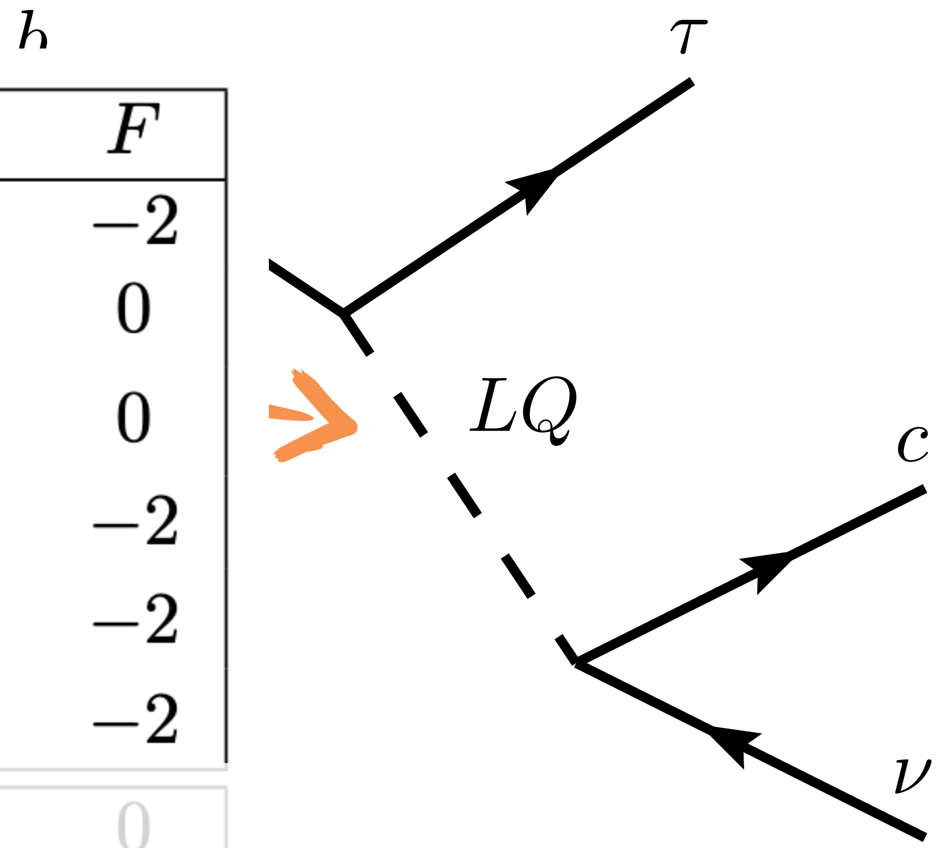

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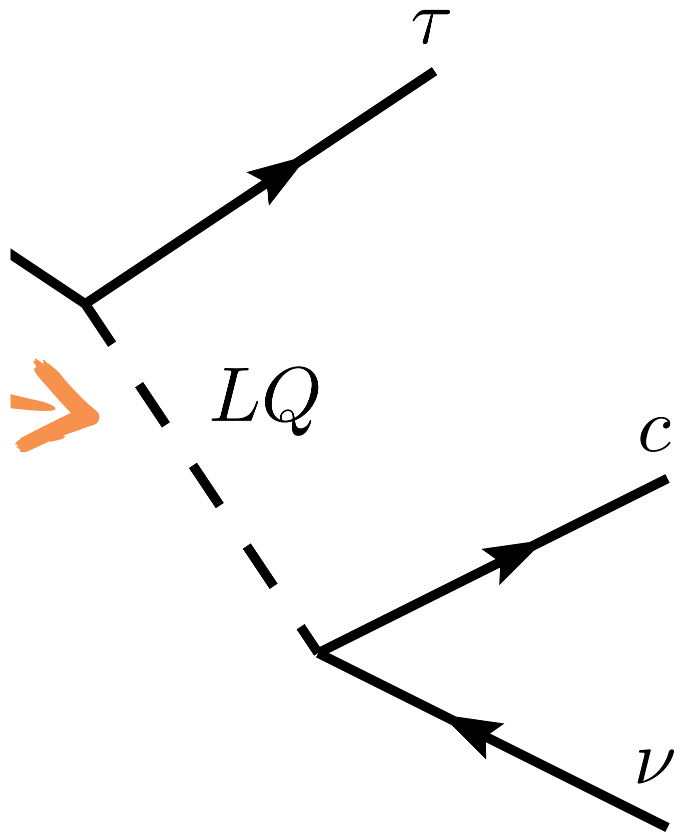

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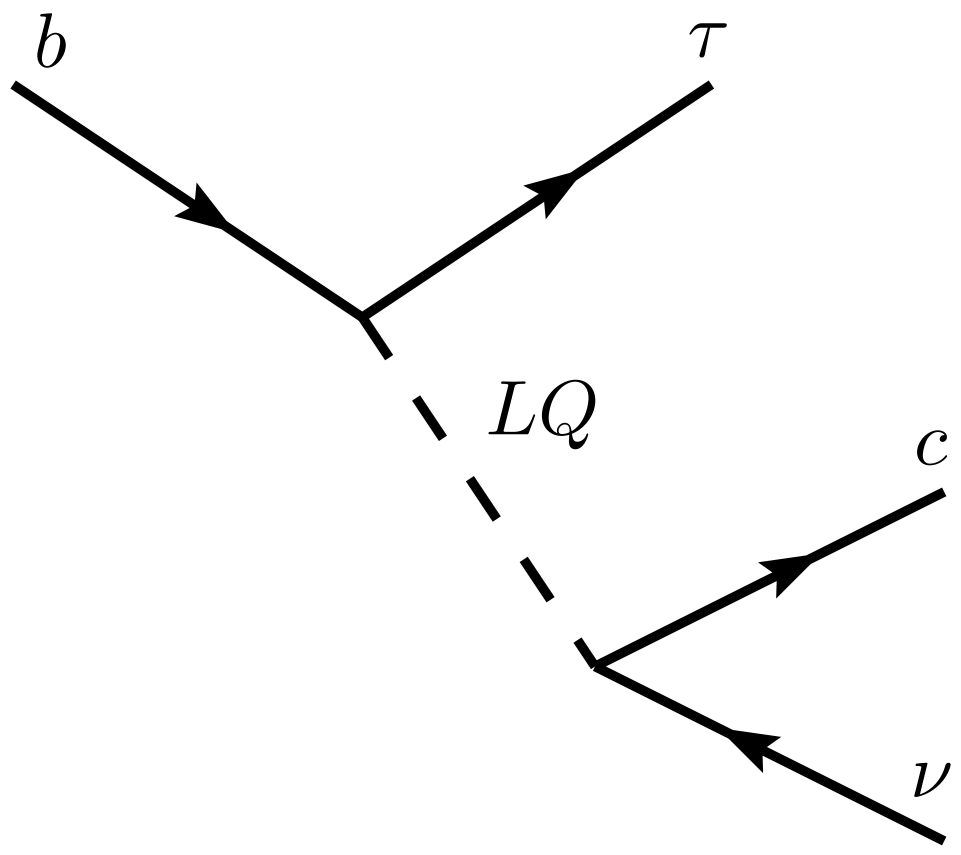
Possible explanations

- Consider minimal coupling texture

  ⇒All three leptoquarks can provide desired effect in $R_{D^{(*)}}$ with only **two non-zero couplings**



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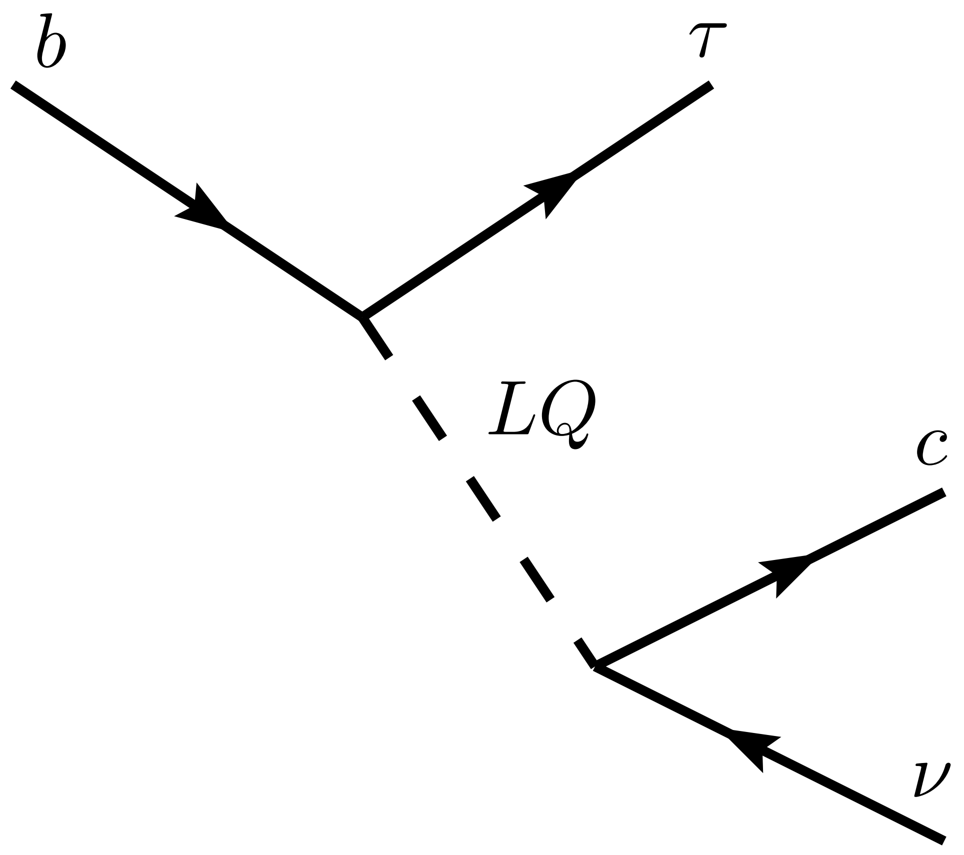

- Consider minimal coupling texture

  ⇒All three leptoquarks can provide desired effect in $R_{D^{(*)}}$ with only two non-zero couplings, **but...**

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Effect in high-p_T tails too large

A RHN has to be added, too severely affecting $B \to K\nu\nu$

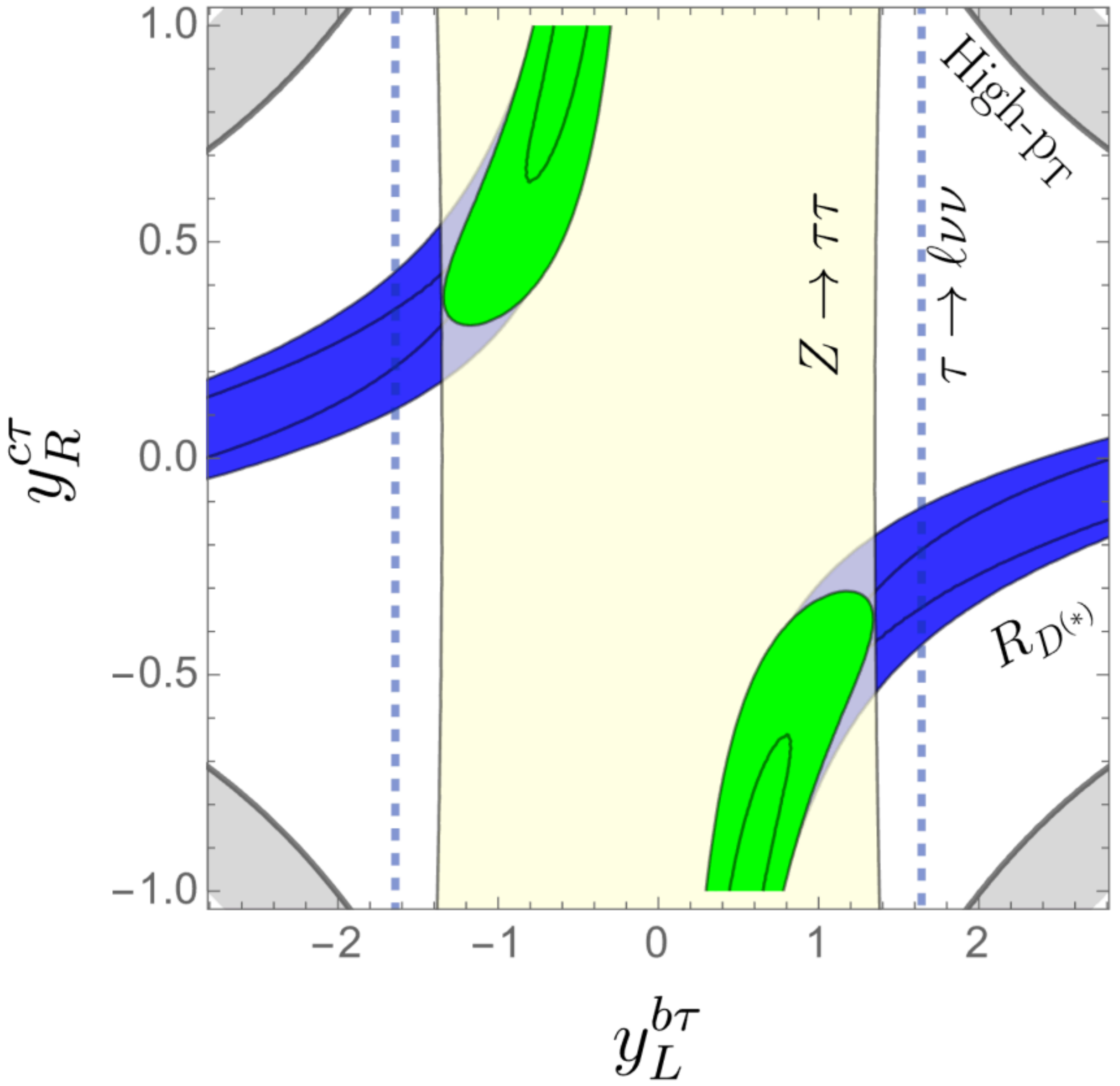
If only left-handed interactions are considered, $B_s - \overline{B}_s$ is too large

Left- and right-handed $S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$

$$\mathcal{L}_{S_1} = y_L^{ij}\, \overline{Q_i^{C,a}}\, \epsilon^{ab}\, L_j^b\, S_1 + y_R^{ij}\, \overline{u_i^C} e_j\, S_1 + \text{h.c.}$$

$$m_{S_1} = 1.5 \text{ TeV}$$

$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_L^{b\tau} \end{pmatrix}, \qquad y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_R^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$



*2σ allowed regions

- Need right-handed interactions

  $\Rightarrow$evade $B_s - \overline{B}_s$ mixing constraint

- Successfully accommodate $R_{D^{(*)}}$ and consistent with other observables

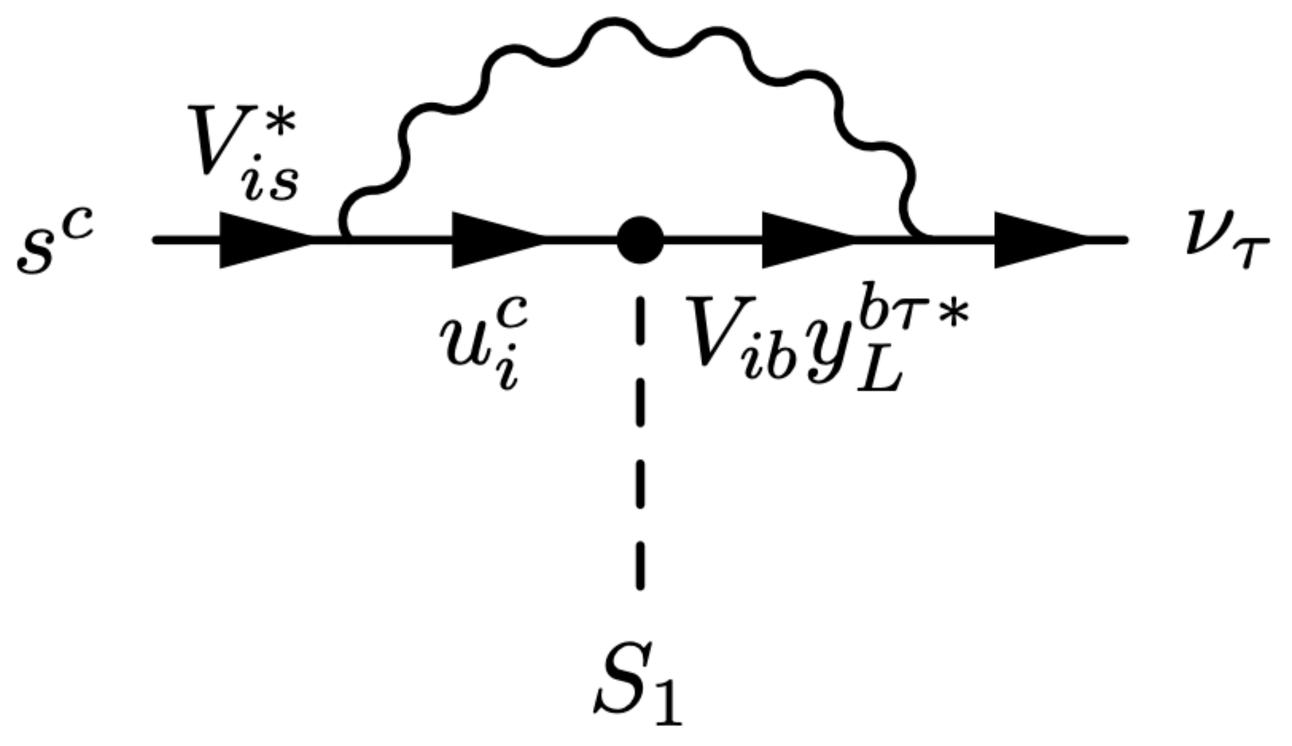
Predictions with S_1

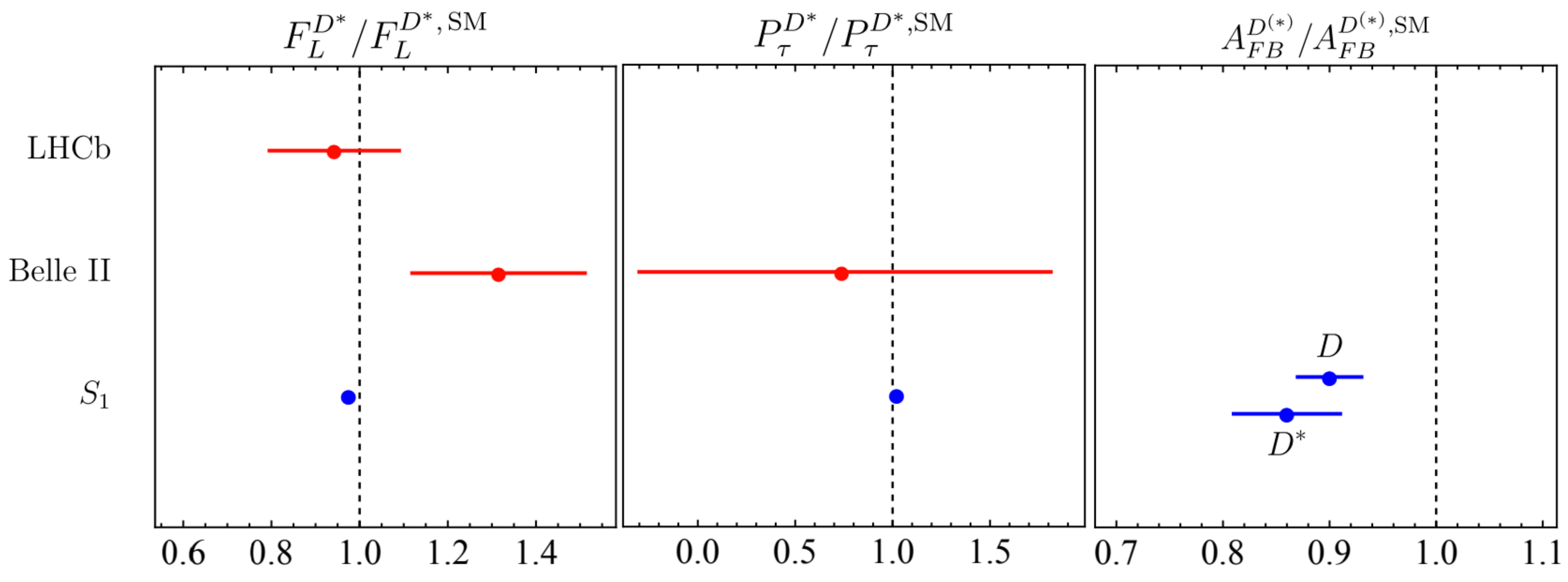
Can be tested in

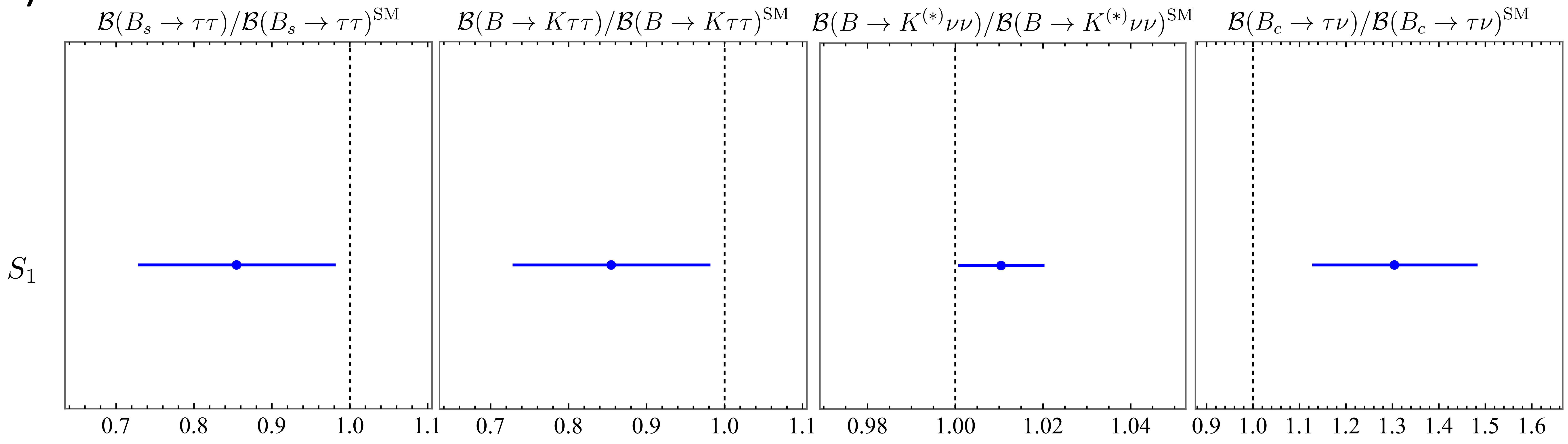
$\Rightarrow B \to D^{(*)}\tau\nu$ angular observables

$\Rightarrow B_c \to \tau\nu$ (tree level effect)

$\Rightarrow B_s \to \tau\tau, B \to K\tau\tau, B \to K^{(*)}\nu\nu$ (loop level effect)







Inert S_1 (right-handed)

- Right-handed interactions

  $\Rightarrow$ no **CKM mixing**

  $\Rightarrow$ evading a lot of constraints from flavour observables

- Model with **only right-handed interactions?**

$$\mathcal{L}_{S_1} = y^R_{ij}\overline{u^C_i}e_j S_1 + \tilde{y}^R_{iN}\overline{d^C_i}N_R\, S_1$$

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$$\mathcal{L}_{S_1} = y^R_{c\tau}\overline{c^C}\tau S_1 + \tilde{y}^R_{bN}\overline{b^C}N_R\, S_1 + \tilde{y}^R_{sN}\overline{s^C}N_R\, S_1$$

Create desired effect in $R_{D^{(*)}}$

Also allows an enhancing effect in $B \to K$'inv'

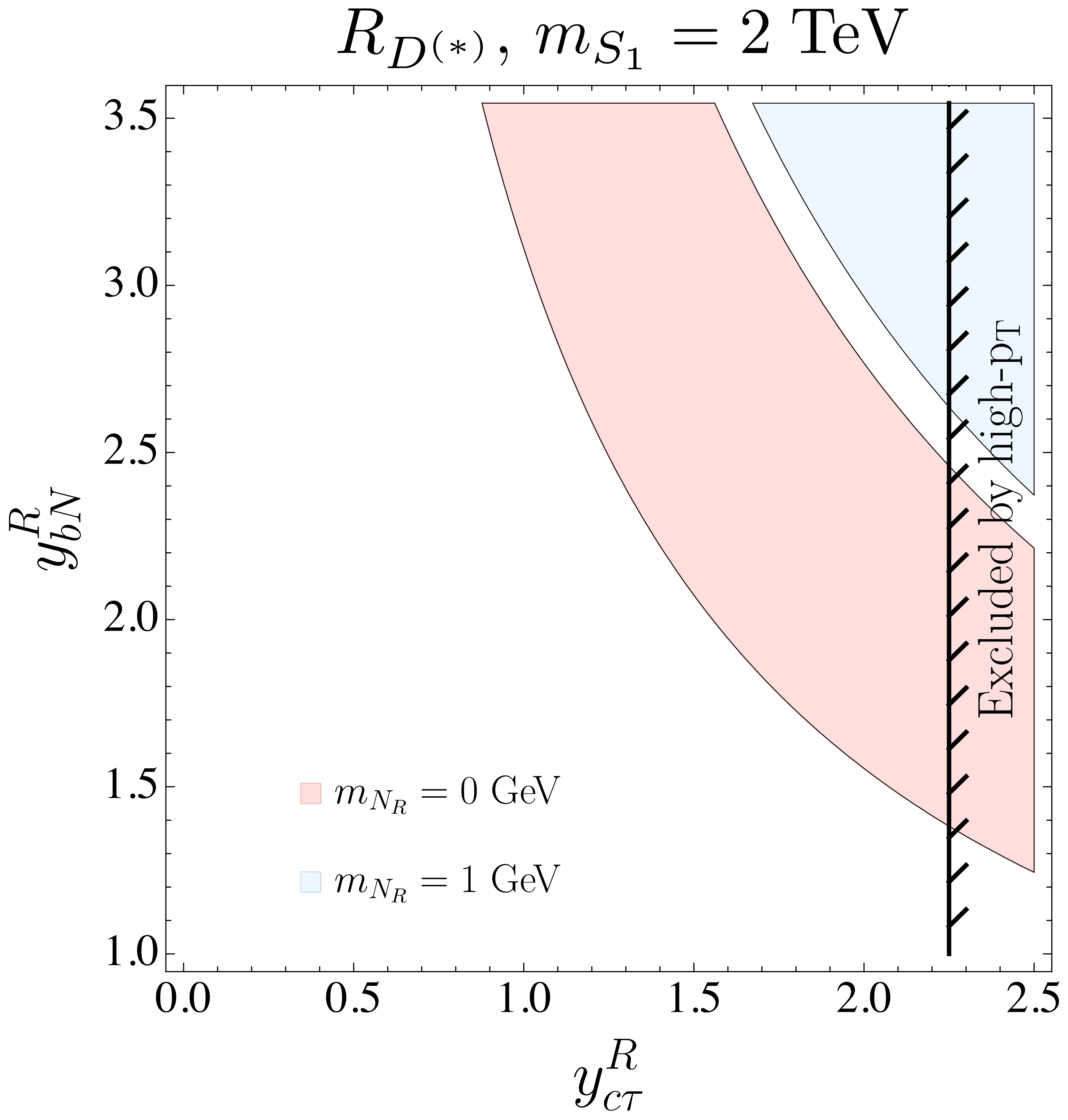
Inert S_1 (right-handed)

- $R_{D^{(*)}}$ can be accomodated

  $\Rightarrow$ up to masses of RHN up to $\sim$1 GeV

- Only RH interactions

  $\Rightarrow$ Evaded $B_s - \overline{B}_s$ mixing, also $Z \to \tau\tau$ and $\tau \to \ell\nu\nu$

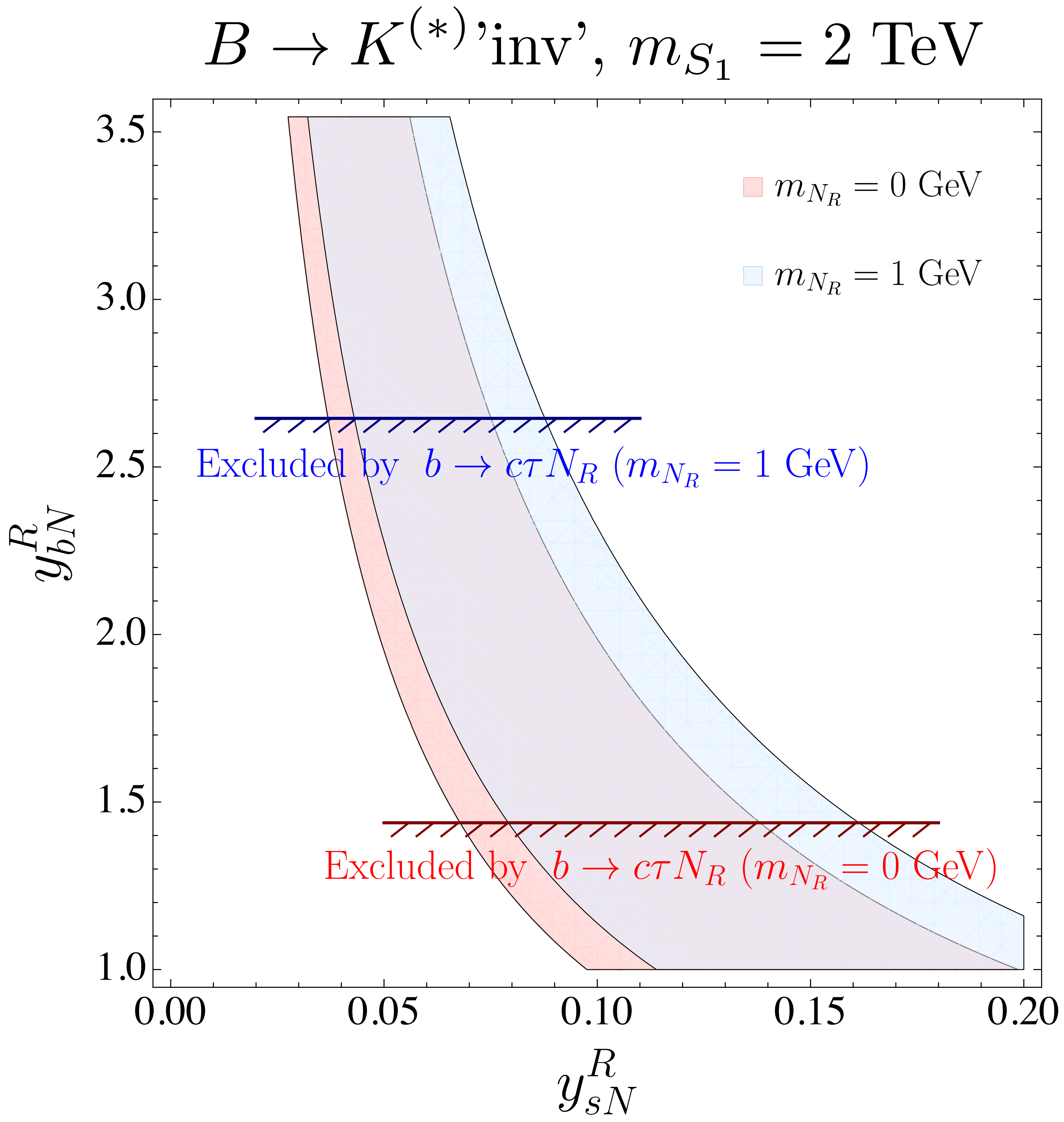


*2σ allowed regions

Inert S_1 (right-handed)

- Excess in $\mathscr{B}(B^+ \to K^+$ 'inv') can also be accomodated

- Besides $R_{D^{(*)}}$ and $B \to K^{(*)}$'inv', practically no other constraining observable



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Inert S_1 (right-handed) -predictions

- For example: $B_c \to \tau$'inv', $B_c \to D_s$ 'inv' , $B_c \to J/\psi\, \tau$ 'inv'

- Particularly interesting:

$\Rightarrow$ Angular observables in $B \to D^{(*)}\tau\nu$ decays, example:

Quantity	SM	m_{N_R}= 0 GeV	0.6 GeV	1 GeV
$P_\tau^{D^*}$	$-0.51(2)$	$-0.39(4)$	$-0.41(3)$	$-0.43(3)$
$F_L^{D^*}$	$0.46(1)$	$0.46(1)$	$0.46(1)$	$0.45(1)$

$\Rightarrow$ $D^0 \to$ 'inv' (branching fraction scales with the $m_{N_R}^2$)

Summary and conclusions

- Hint for the New Physics in $b \to c\ell\nu$ transitions

- Explored different minimal TeV-scale LQ models

  ⇒Only two are viable:

  - S_1 with left and right-handed interactions

    ⇒Plenty of observables affected; $R_{D^{(*)}}, Z \to \tau\tau, \nu\nu, \tau \to \ell\nu\nu$, High-$p_T$, FB asymmetry...

  - S_1 with only right-handed interactions, with the introduction of **right-handed neutrino(s)**

    ⇒Few observables affected, **but has a specific signature in angular observables in $B \to D^{(*)}\tau\nu$**

    ⇒More specifically, the presence of **RHN can be inferred from P_τ**

Thank you for your attention!