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

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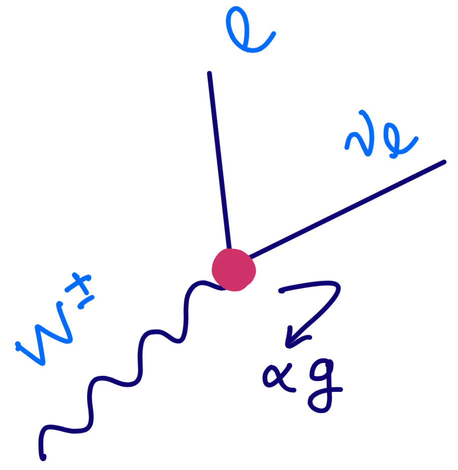
(based on 2404.16772 with D. Bečirević, S. Fajfer and N. Košnik)

Lovre Pavičić 4.10.2024

Motivation

- Standard Model cannot address Dark Matter, BAU, Neutrino masses...

  $\Rightarrow$ Need for **New Physics**: Direct searches at LHC - **Indirect searches** at low energy

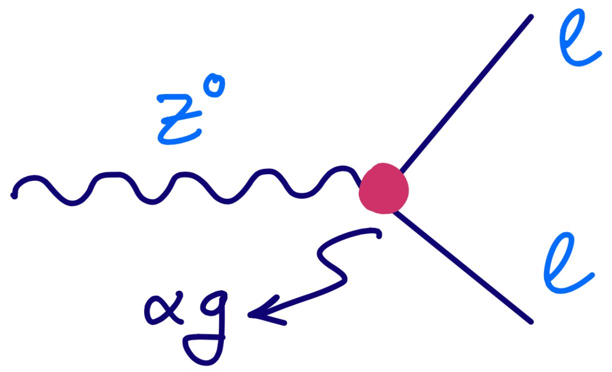


- Indirect searches - Test SM (accidental) symmetries

Flavour physics: **test lepton flavour universality**

W^+ DECAY MODES		Fraction (Γ_i/Γ)
$\ell^+\nu$	[b]	(10.86 ± 0.09) %
$e^+\nu$		(10.71 ± 0.16) %
$\mu^+\nu$		(10.63 ± 0.15) %
$\tau^+\nu$		(11.38 ± 0.21) %
hadrons		(67.41 ± 0.27) %

Z DECAY MODES		Fraction (Γ_i/Γ)
e^+e^-	[h]	(3.3632 ± 0.0042) %
$\mu^+\mu^-$	[h]	(3.3662 ± 0.0066) %
$\tau^+\tau^-$	[h]	(3.3696 ± 0.0083) %
$\ell^+\ell^-$	[b,h]	(3.3658 ± 0.0023) %



[PDG 2024]

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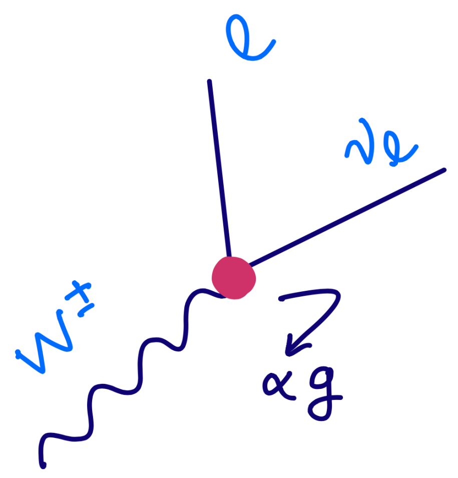

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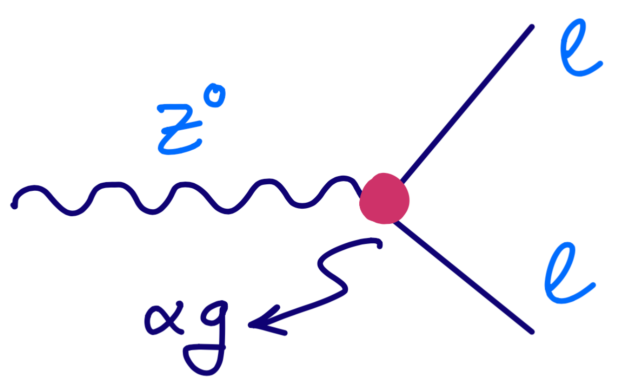
[PDG 2024]

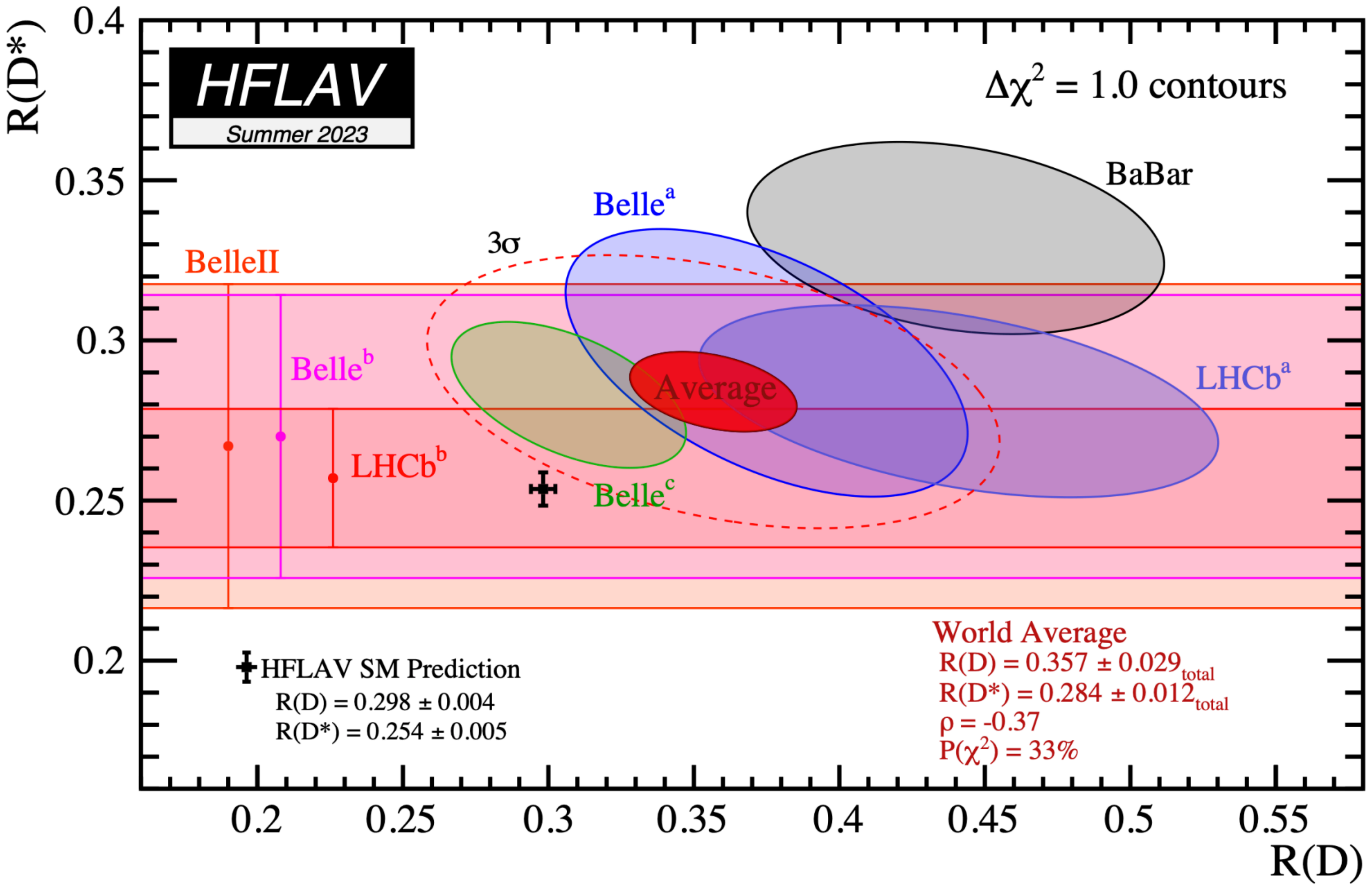
- BUT: current measurements of **semi-leptonic B-meson** decays appear to tell a **different story**!



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

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

- Test of lepton flavour universality
- Theoretically clean; **hadronic uncertainties cancel** in the ratio
- SM predictions significantly smaller than experiment, **combined deviation:** $\sim 3.3\,\sigma$



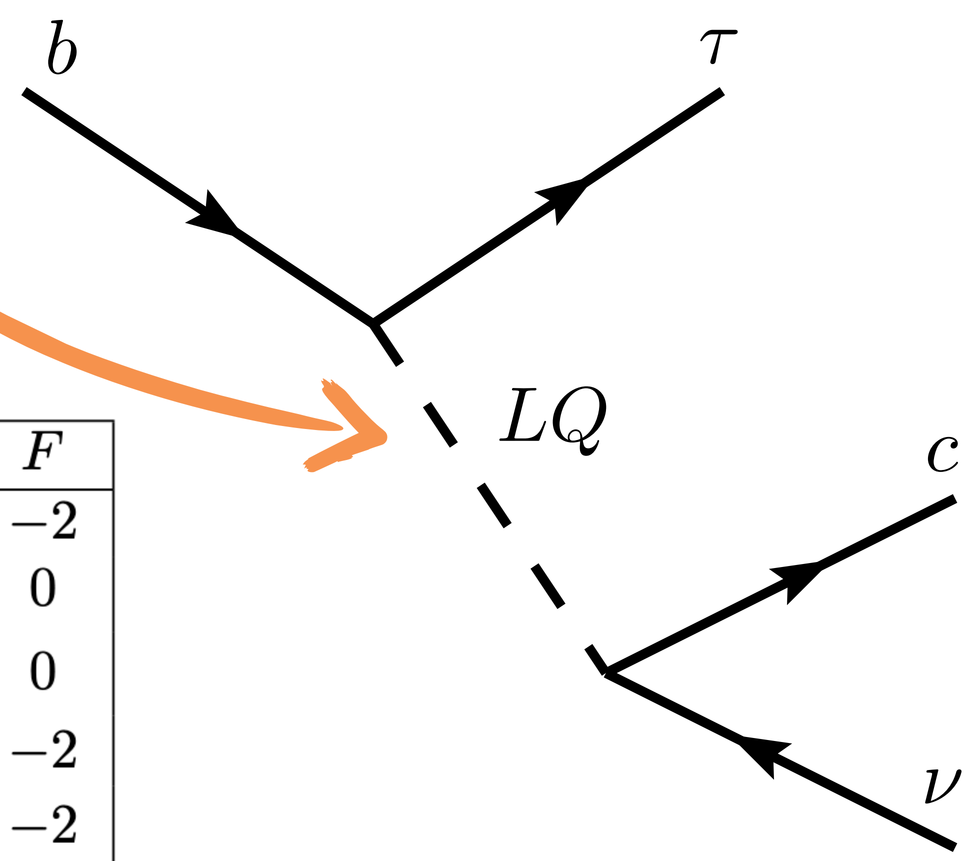
$\Rightarrow$ Violation of LFU? **New Physics** coupled to b and τ?

Possible explanations

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

EFT study - $\Lambda_{NP} \simeq m_{NP}/C_{NP} \sim \mathcal{O}(1-3)\text{TeV}$

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



- **Or Leptoquarks!**

$(SU(3), SU(2), U(1))$	Spin	Symbol	Type	F
$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	0	S_3	$LL\,(S_1^L)$	-2
$(\mathbf{3}, \mathbf{2}, 7/6)$	0	R_2	$RL\,(S_{1/2}^L)$, $LR\,(S_{1/2}^R)$	0
$(\mathbf{3}, \mathbf{2}, 1/6)$	0	$\tilde{R}_2$	$RL\,(\tilde{S}_{1/2}^L)$, $\overline{LR}\,(\tilde{S}_{1/2}^{\bar{L}})$	0
$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	0	$\tilde{S}_1$	$RR\,(\tilde{S}_0^R)$	-2
$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	0	S_1	$LL\,(S_0^L)$, $RR\,(S_0^R)$, $\overline{RR}\,(S_0^{\bar{R}})$	-2
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(1603.04993)

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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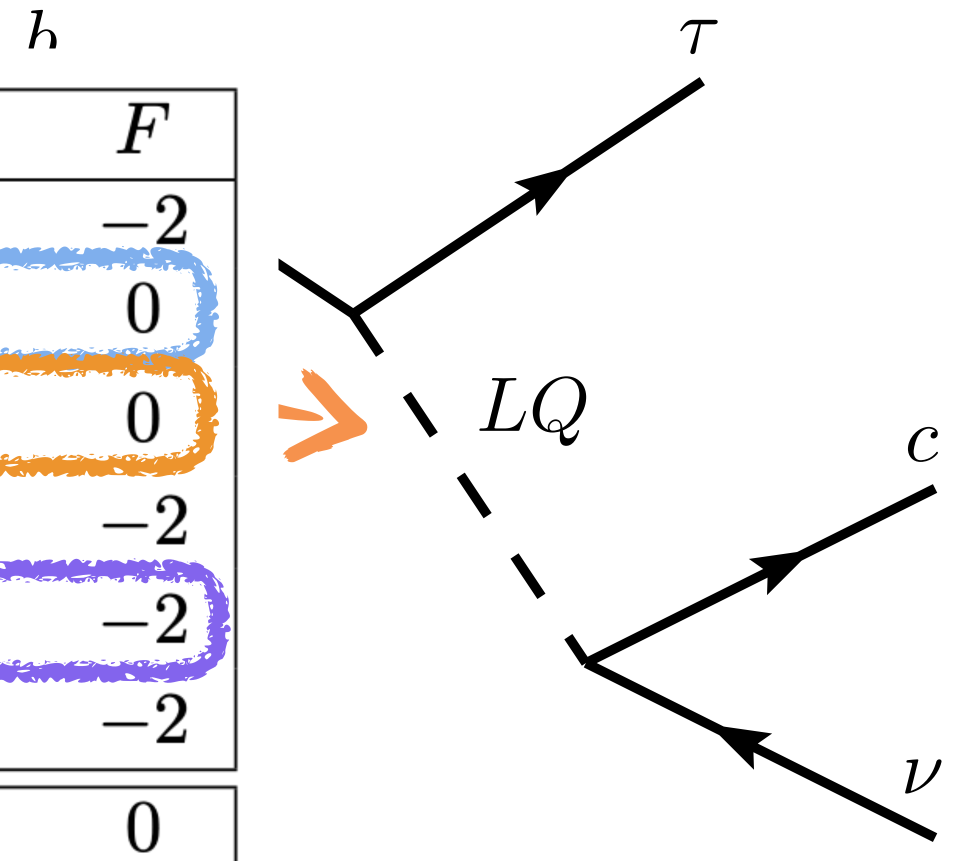

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Constraints on LQ models

- **Collider bounds**: Direct searches ($M_{LQ} \gtrsim 1.5$ TeV), **high-p_T** tails in $pp \to \tau\tau, pp \to \tau\nu$

- **Electroweak precision observables:** $Z \to \tau\tau, Z \to \nu\nu, \tau \to \ell\nu\bar{\nu}$

- B**-physics observables**: $B_s - \overline{B}_s$ mixing, $B \to K\nu\bar{\nu}$, $B_c \to \tau\nu$, $B_s \to \tau\tau$, $B \to K\tau\tau$, angular observables

R_2

- Consider minimal coupling texture

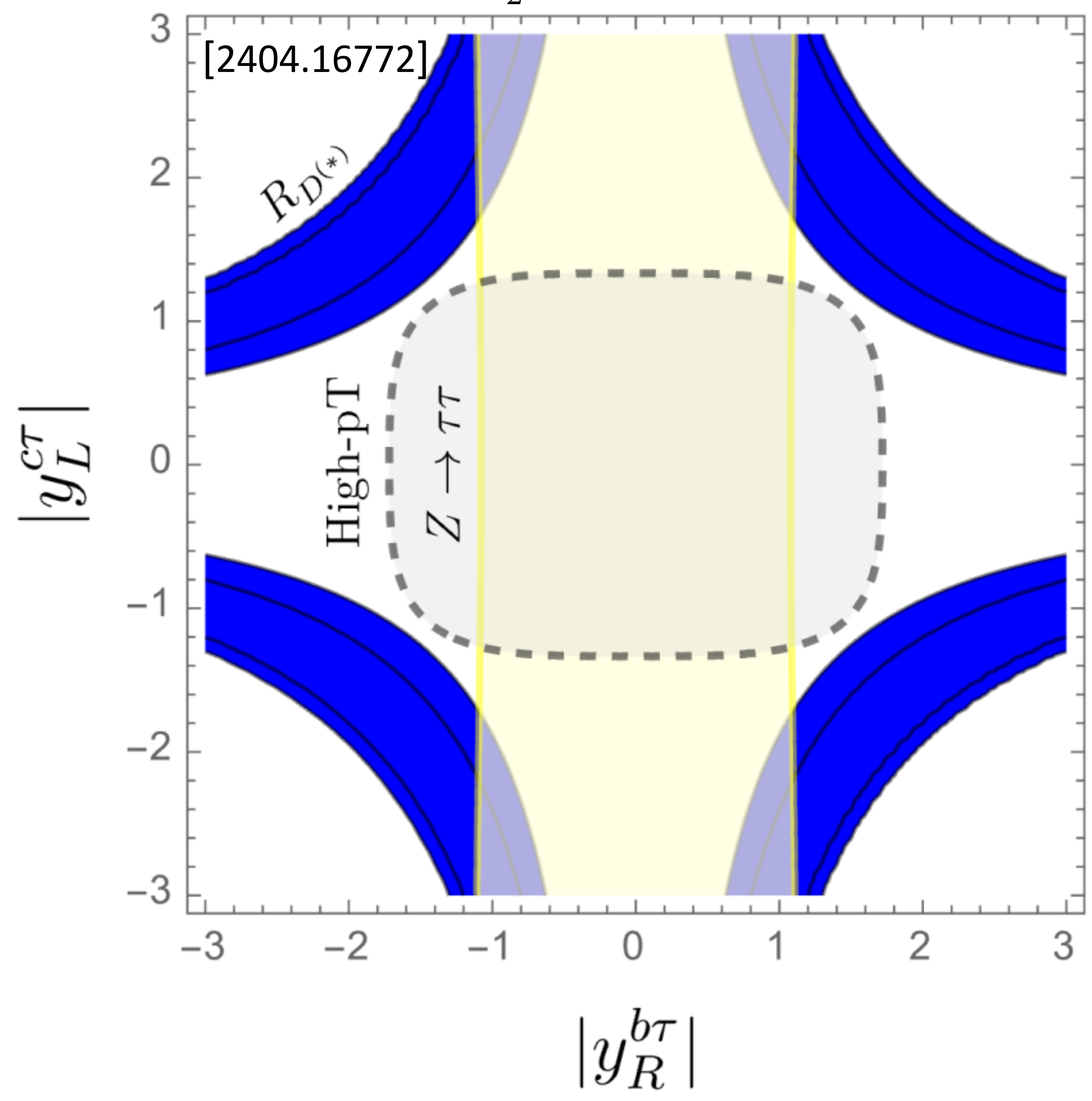
$$y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix}, \qquad y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

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

- But: high-p_T - data excludes the viable parameter space :(

$$\mathcal{L}_{R_2} = y_R^{ij}\, \bar{Q}_i^a e_j R_2^a \;+\; y_L^{ij}\, \bar{u}_{Ri} R_2^{T,a} \epsilon^{ab} L_j^b + \text{h.c.}$$

$m_{R_2} = 1.5\,\text{TeV}$



*2σ allowed regions

$\tilde{R}_2$

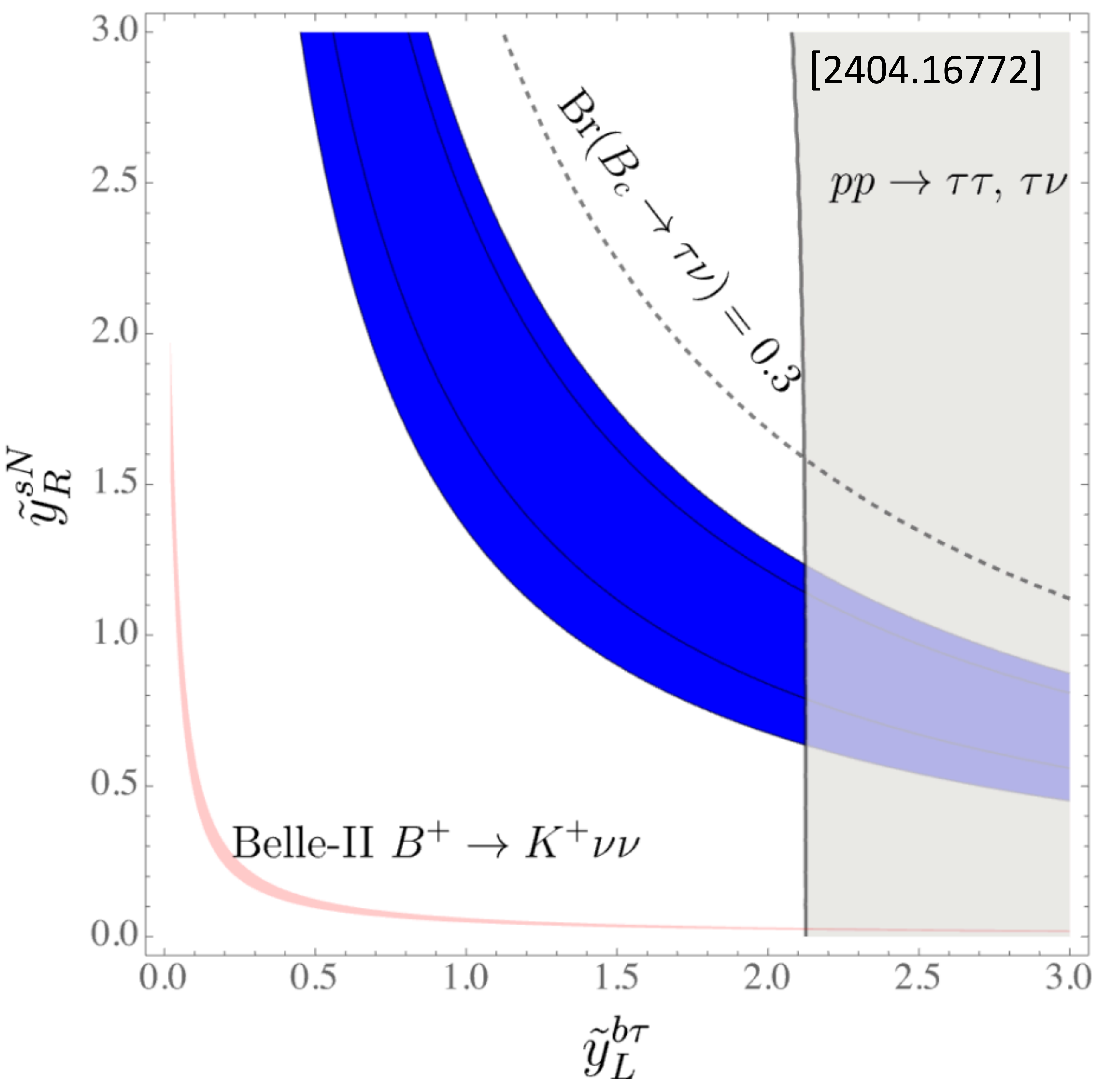
$$\mathcal{L} = -\tilde{y}_L^{ij}\,\overline{d}^i\,\tilde{R}_2^a \epsilon^{ab} L^{j,b} + \tilde{y}_R^{iN}\,\overline{Q}^{i,a}\,\tilde{R}_2^a N_R + \text{h.c.}$$

$$m_{\tilde{R}_2} = 1.5\ \text{TeV}$$

$$\tilde{y}_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \tilde{y}_L^{b\tau} \end{pmatrix}, \qquad \tilde{y}_R = \begin{pmatrix} 0 \\ \tilde{y}_R^{sN} \\ 0 \end{pmatrix}$$

- Again, $R_{D^{(*)}}$ can be accommodated :)
  * if a **right-handed neutrino** is added!

- But $B \to K\nu\nu$ is too severely affected



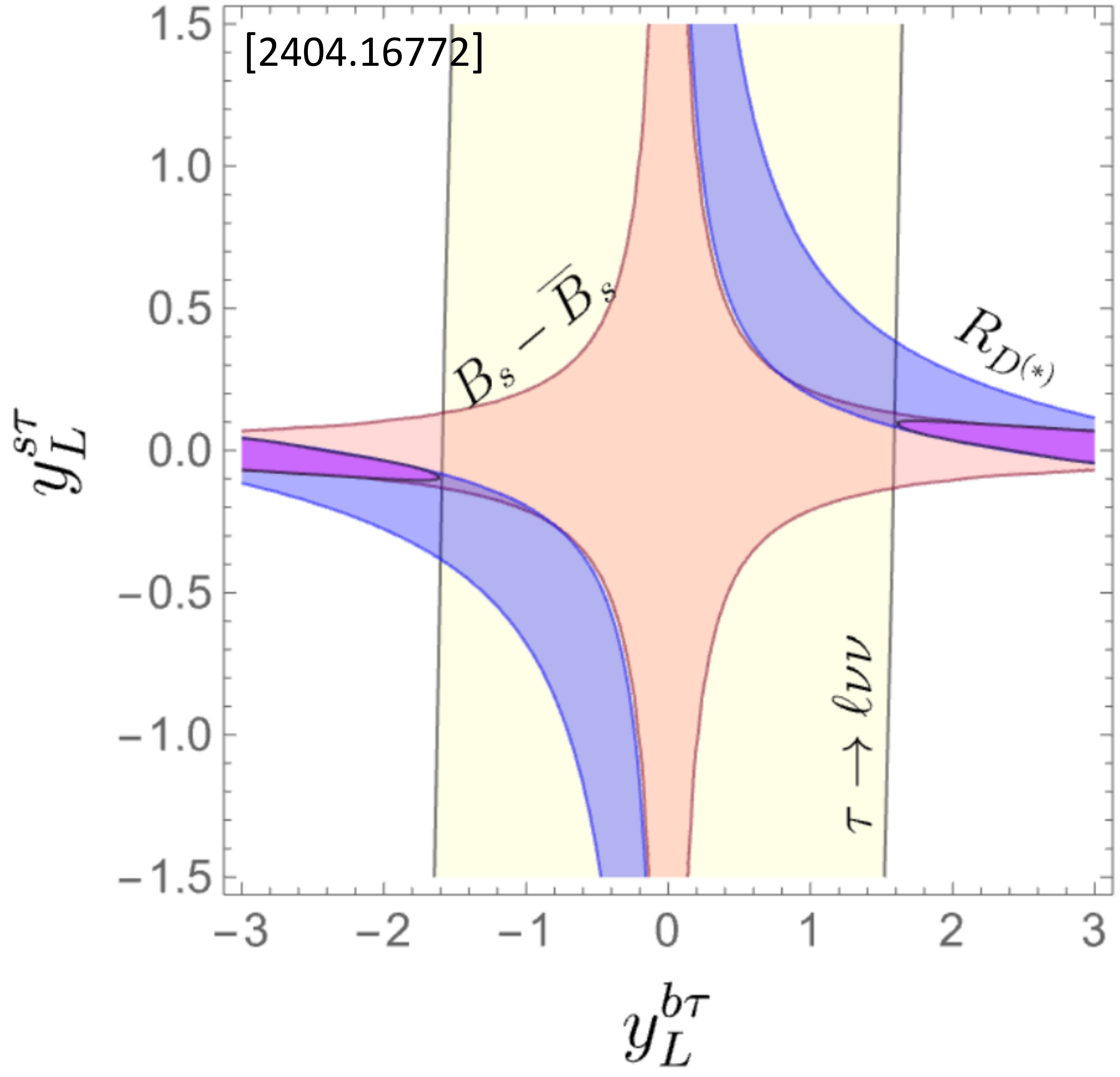
*2σ allowed regions

Left-handed S_1

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

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

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



*2σ allowed regions

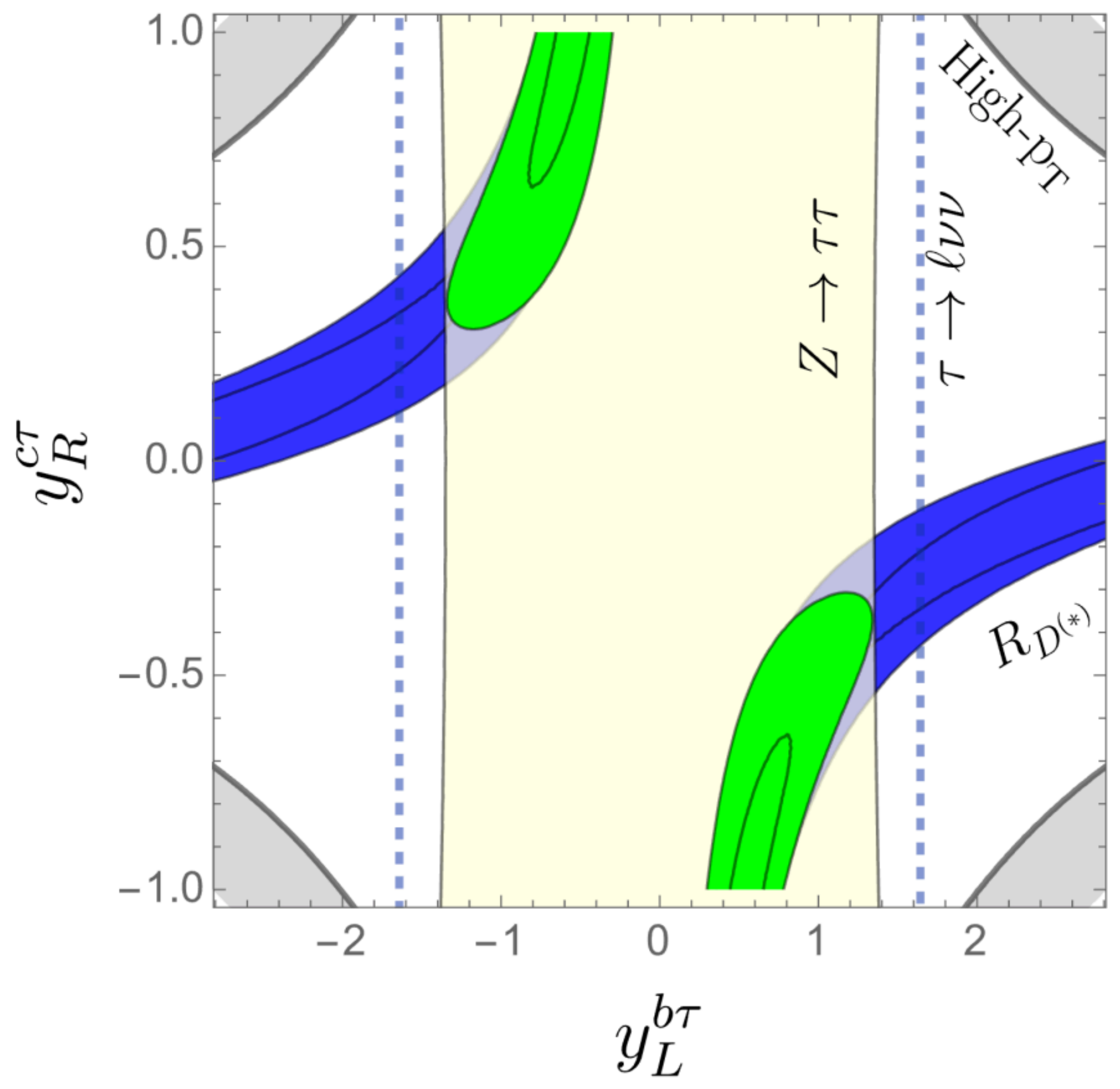
- Once again, $R_{D^{(*)}}$ can be accommodated
- But this time the effect in $B_s - \overline{B}_s$ is slightly too large

Left- and right-handed S_1

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

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

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



*2σ allowed regions

- Need right-handed couplings

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

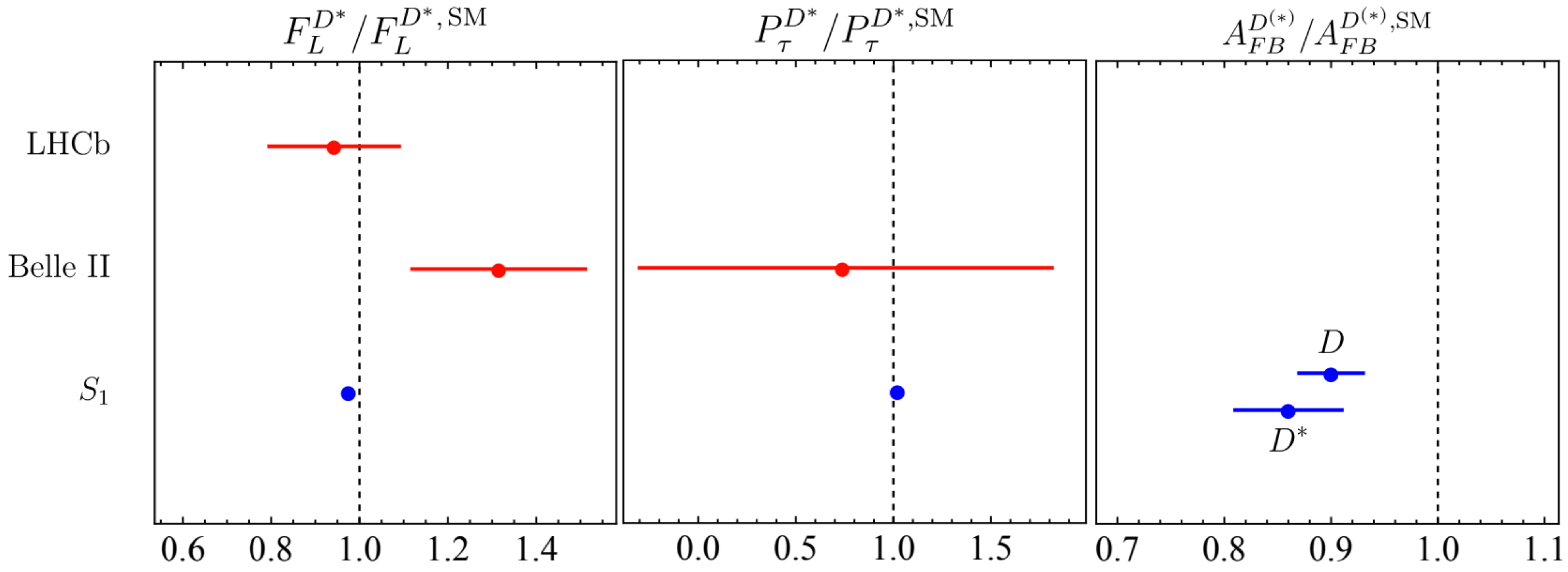
- Successfully accommodate $R_{D^{(*)}}$ and consistent with other observables :)

Predictions with S_1

- Explored 3 different minimal TeV-scale LQ models

  $\Rightarrow$Only S_1 with left and right-handed couplings **phenomenologically viable**

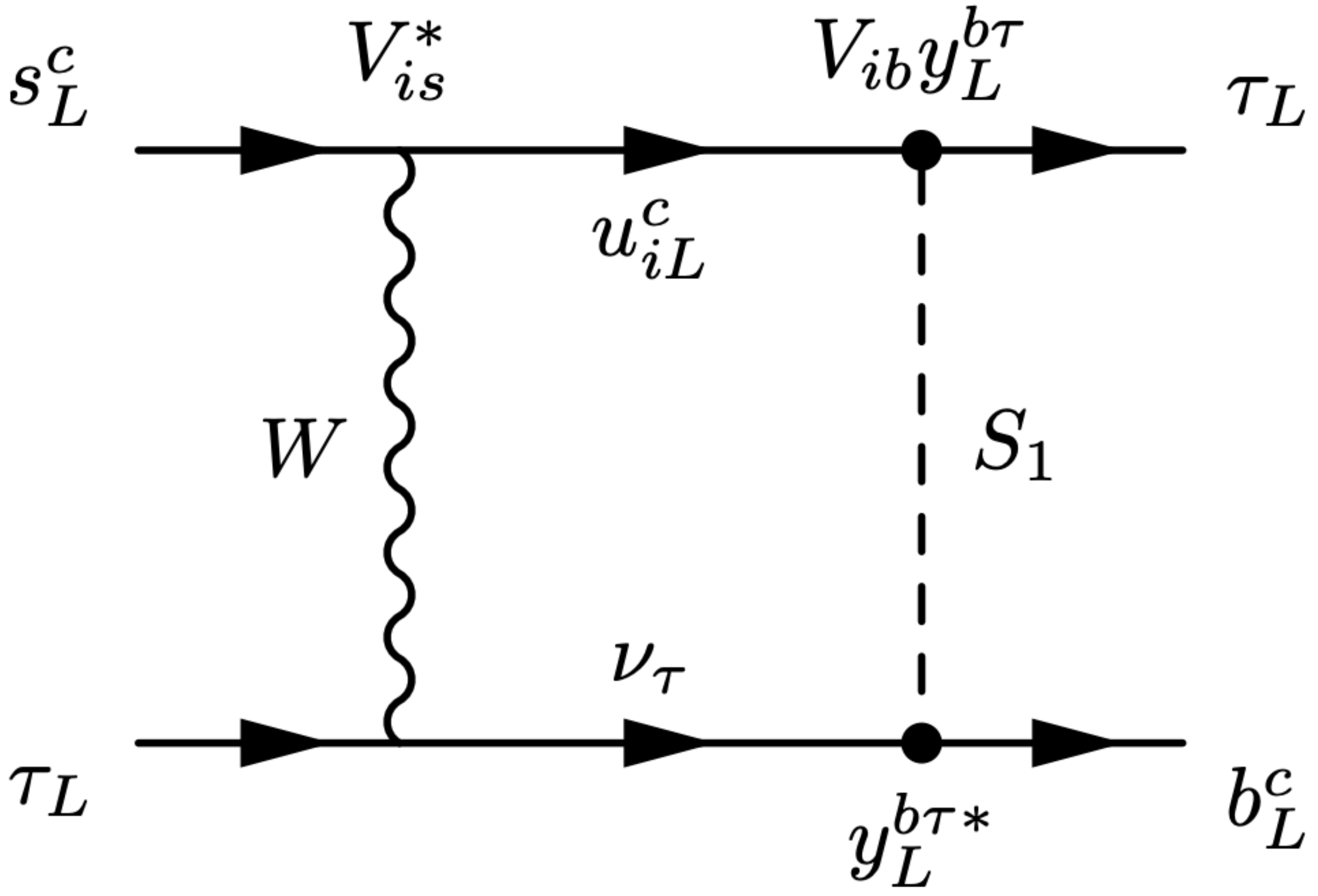
- **Can be tested** in $B \to D^{(*)}\tau\nu$ angular observables

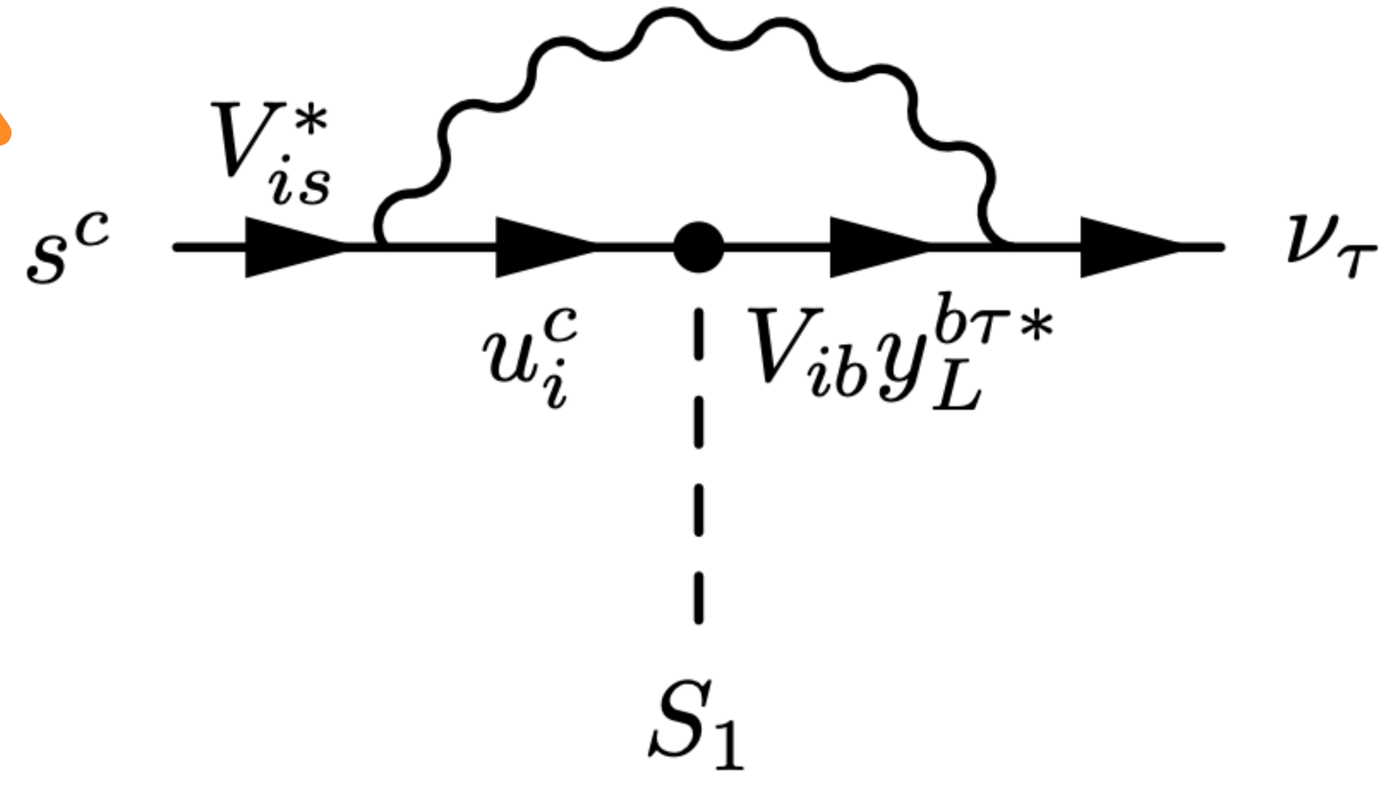


Predictions with S_1

- Tree level effect in $b \to c\tau\nu$ $\Rightarrow$ $\dfrac{\mathcal{B}(B_c \to \tau\nu)^{S_1}}{\mathcal{B}(B_c \to \tau\nu)^{\mathrm{SM}}} \in [1.13, 1.48]$

- Loop effects in $b \to s\ell\ell$





$\dfrac{\mathcal{B}(B_s \to \tau\tau)^{S_1}}{\mathcal{B}(B_s \to \tau\tau)^{\mathrm{SM}}} \in [0.73, 0.98]\,,$ $\dfrac{\mathcal{B}(B \to K\tau\tau)^{S_1}}{\mathcal{B}(B \to K\tau\tau)^{\mathrm{SM}}} \in [0.73, 0.98]$ $\dfrac{\mathcal{B}(B \to K^{(*)}\nu\nu)^{S_1}}{\mathcal{B}(B \to K^{(*)}\nu\nu)^{\mathrm{SM}}} \in [1.001, 1.02]$

Inert S_1 (right-handed) - preliminary

- Right-handed couplings

  $\Rightarrow$ no **CKM mixing**

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

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

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

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

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

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

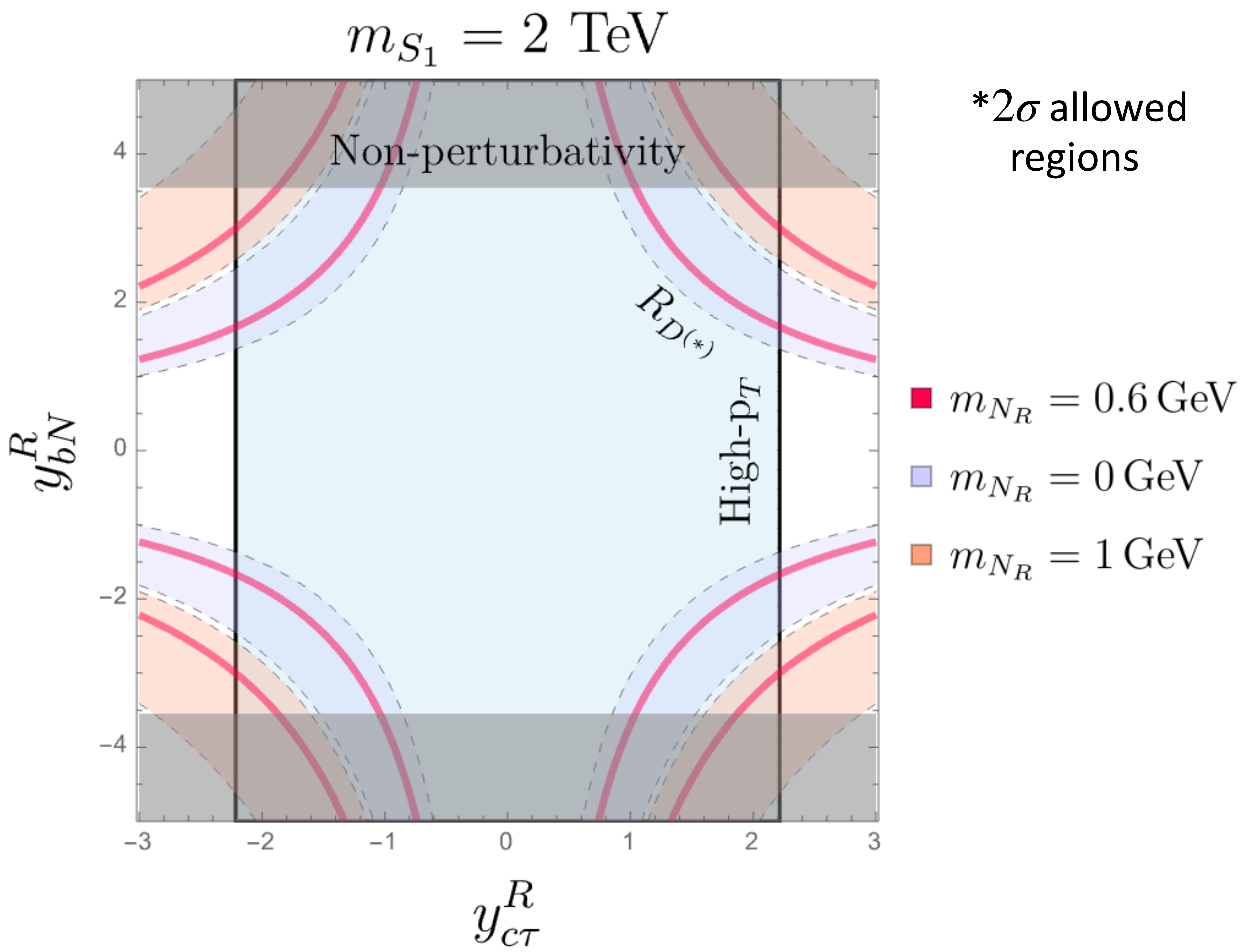
Also allows an enhancing effect in $B \rightarrow K^{(*)}\nu\nu$

Inert S_1 (right-handed) - preliminary

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

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

- Apart from high-p_T tails, $R_{D^{(*)}}$ **is only constraining observable**
- $B \to K^{(*)}\nu\nu$ sets bounds on $|y^R_{sN} y^R_{bN}|$ and **it is decoupled from $R_{D^{(*)}}$**



Summary and conclusions

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

- Explored 4 different minimal TeV-scale LQ models

  ⇒Only two are viable:

  - S_1 with left and right-handed couplings

    ⇒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 couplings, with the introduction of **right-handed neutrino(s)**

    ⇒Quite 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!