IJCLab

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

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

UNIVERZA V LJUBLJANI | FMF Fakulteta za matematiko in fiziko

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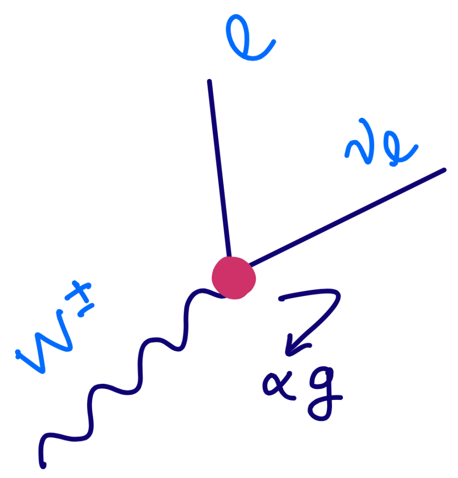
(based on 2404.16772 and 2410.23257 with D. Bečirević, S. Fajfer and N. Košnik)

Lovre Pavičić 14.11.2024

Motivation

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

  ⇒ Need for **New Physics**: Direct searches at LHC - **Indirect searches** at low energy

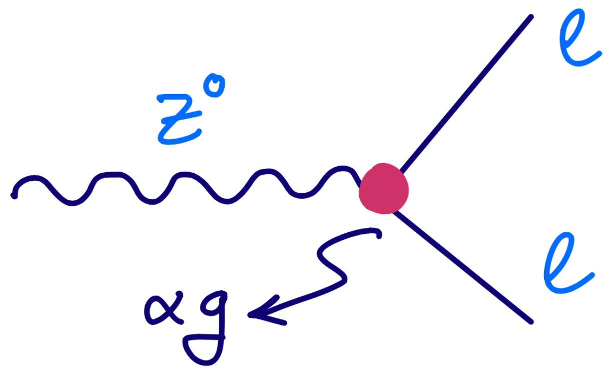


- Indirect searches - Test SM (accidental) symmetries

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) %

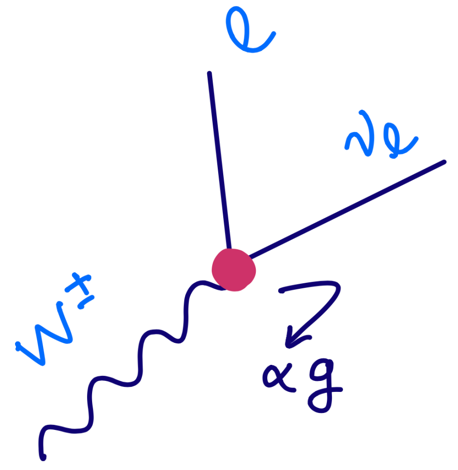


[PDG 2024]

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

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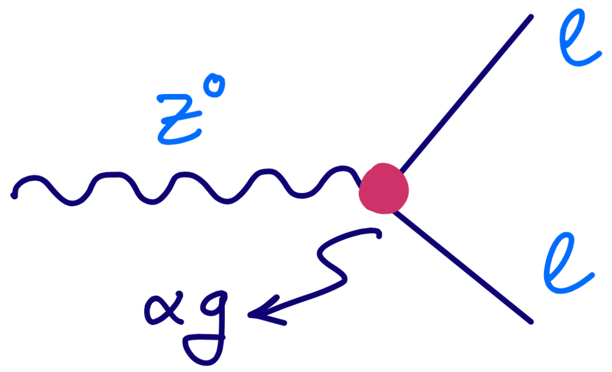
$\tau^+\tau^-$	[h]	(3.3696 ± 0.0083) %
$\ell^+\ell^-$	[b,h]	(3.3658 ± 0.0023) %

[PDG 2024]

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



B-meson decays

Powerful probes of New Physics

- **Theoretically clean** - b-quark is heavy: HQET applies, precise predictions thanks to non-perturbative QCD possible

- **Experimentally accessible** - at LHC mostly produced in forward region (design of LHCb), also dedicated "B-factories" (Belle II, BaBar)

- **Charged current decays** used to measure CKM parameters ($|V_{cb}|$, $|V_{ub}|$, δ_{CP}, γ)

- **Long lifetime** - measure B and B_s oscilations, insight on CP violation in the SM

- Hundreds of decay channels to explore

B-meson decays

Powerf

- The ... ies, precise predictions thanks to n...
- Exp ... ed in forward region (design of LHC...)
- Cha ... rameters ($|V_{cb}|, |V_{ub}|, \delta_{CP}, \gamma$)
- Lon ... ht on CP violation in the SM
- Hur

B^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Semileptonic and leptonic modes				
$\ell^+ \nu_\ell X$	[lll]	(10.99 ± 0.28) %		–
$e^+ \nu_e X_c$		(10.8 ± 0.4) %		–
$D \ell^+ \nu_\ell X$		(9.7 ± 0.7) %		–
$\overline{D}^0 \ell^+ \nu_\ell$	[lll]	(2.35 ± 0.09) %		2310
$\overline{D}^0 \tau^+ \nu_\tau$		(7.7 ± 2.5) $\times 10^{-3}$		1911
$\overline{D}^*(2007)^0 \ell^+ \nu_\ell$	[lll]	(5.66 ± 0.22) %		2258
$\overline{D}^*(2007)^0 \tau^+ \nu_\tau$		(1.88 ± 0.20) %		1839
$D^- \pi^+ \ell^+ \nu_\ell$		(4.4 ± 0.4) $\times 10^{-3}$		2306
$\overline{D}_0^*(2420)^0 \ell^+ \nu_\ell$, $\overline{D}_0^{*0} \to D^- \pi^+$		(2.5 ± 0.5) $\times 10^{-3}$		–
$\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell$, $\overline{D}_2^{*0} \to D^- \pi^+$		(1.53 ± 0.16) $\times 10^{-3}$		2065
$D^{(*)} n \pi \ell^+ \nu_\ell (n \geq 1)$		(1.88 ± 0.25) %		–
$D^{*-} \pi^+ \ell^+ \nu_\ell$		(6.0 ± 0.4) $\times 10^{-3}$		2254
$\overline{D}_1(2420)^0 \ell^+ \nu_\ell$, $\overline{D}_1^0 \to D^{*-} \pi^+$		(3.03 ± 0.20) $\times 10^{-3}$		2084
$\overline{D}_1'(2430)^0 \ell^+ \nu_\ell$, $\overline{D}_1'^0 \to D^{*-} \pi^+$		(2.7 ± 0.6) $\times 10^{-3}$		–
$\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell$, $\overline{D}_2^{*0} \to D^{*-} \pi^+$		(1.01 ± 0.24) $\times 10^{-3}$	S=2.0	2065
$\overline{D}^0 \pi^+ \pi^- \ell^+ \nu_\ell$		(1.7 ± 0.4) $\times 10^{-3}$		2301
$\overline{D}^{*0} \pi^+ \pi^- \ell^+ \nu_\ell$		(8 ± 5) $\times 10^{-4}$		2248
$D_s^{(*)-} K^+ \ell^+ \nu_\ell$		(6.1 ± 1.0) $\times 10^{-4}$		–
$D_s^- K^+ \ell^+ \nu_\ell$		(3.0 $^{+1.4}_{-1.2}$) $\times 10^{-4}$		2242

HTTP://PDG.LBL.GOV   Page 73   Created: 8/28/2020 18:31

B-meson decays

Powerf

- The
  to n
- Exp
  LHC
- Cha
- Lon
- Hur

B^+ DECAY MODES		Fraction (Γ_i/Γ)	S Conf	
Semileptonic and leptonic modes				
$\ell^+ \nu_\ell X$	[///]	(10.99 ± 0.28) %		
$e^+ \nu_e X_c$		(10.8 ± 0.4) %		
$D \ell^+ \nu_\ell X$		(9.7 ± 0.7) %		
$\overline{D}^0 \ell^+ \nu_\ell$	[///]	(2.35 ± 0.09) %		
$\overline{D}^0 \tau^+ \nu_\tau$		(7.7 ± 2.5) × 10^{-3}		
$\overline{D}^*(2007)^0 \ell^+ \nu_\ell$	[///]	(5.66 ± 0.22) %		
$\overline{D}^*(2007)^0 \tau^+ \nu_\tau$		(1.88 ± 0.20) %		
$D^- \pi^+ \ell^+ \nu_\ell$		(4.4 ± 0.4) × 10^{-3}		
$\overline{D}_0^*(2420)^0 \ell^+ \nu_\ell$, $\overline{D}_0^{*0} \to D^- \pi^+$		(2.5 ± 0.5) × 10^{-3}		
$\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell$, $\overline{D}_2^{*0} \to D^- \pi^+$		(1.53 ± 0.16) × 10^{-3}		
$D^{(*)} n\pi \ell^+ \nu_\ell (n \geq 1)$		(1.88 ± 0.25) %		
$D^{*-} \pi^+ \ell^+ \nu_\ell$		(6.0 ± 0.4) × 10^{-3}		
$\overline{D}_1(2420)^0 \ell^+ \nu_\ell$, $\overline{D}_1^0 \to D^{*-} \pi^+$		(3.03 ± 0.20) × 10^{-3}		
$\overline{D}_1'(2430)^0 \ell^+ \nu_\ell$, $\overline{D}_1'^0 \to D^{*-} \pi^+$		(2.7 ± 0.6) × 10^{-3}		
$\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell$, $\overline{D}_2^{*0} \to D^{*-} \pi^+$		(1.01 ± 0.24) × 10^{-3}		
$\overline{D}^0 \pi^+ \pi^- \ell^+ \nu_\ell$		(1.7 ± 0.4) × 10^{-3}		
$\overline{D}^{*0} \pi^+ \pi^- \ell^+ \nu_\ell$		(8 ± 5) × 10^{-4}		
$D_s^{(*)-} K^+ \ell^+ \nu_\ell$		(6.1 ± 1.0) × 10^{-4}		–
$D_s^- K^+ \ell^+ \nu_\ell$		(3.0 $^{+1.4}_{-1.2}$) × 10^{-4}		2242

$D_s^{*-} K^+ \ell^+ \nu_\ell$		(2.9 ± 1.9) × 10^{-4}		2185
$\pi^0 \ell^+ \nu_\ell$		(7.80 ± 0.27) × 10^{-5}		2638
$\eta \ell^+ \nu_\ell$		(3.9 ± 0.5) × 10^{-5}		2611
$\eta' \ell^+ \nu_\ell$		(2.3 ± 0.8) × 10^{-5}		2553
$\omega \ell^+ \nu_\ell$	[///]	(1.19 ± 0.09) × 10^{-4}		2582
$\rho^0 \ell^+ \nu_\ell$	[///]	(1.58 ± 0.11) × 10^{-4}		2583
$p \overline{p} \ell^+ \nu_\ell$		(5.8 $^{+2.6}_{-2.3}$) × 10^{-6}		2467
$p \overline{p} \mu^+ \nu_\mu$		< 8.5 × 10^{-6}	CL=90%	2446
$p \overline{p} e^+ \nu_e$		(8.2 $^{+4.0}_{-3.3}$) × 10^{-6}		2467
$e^+ \nu_e$		< 9.8 × 10^{-7}	CL=90%	2640
$\mu^+ \nu_\mu$		2.90 × 10^{-07} to 1.07 × 10^{-06}	CL=90%	2639
$\tau^+ \nu_\tau$		(1.09 ± 0.24) × 10^{-4}	S=1.2	2341
$\ell^+ \nu_\ell \gamma$		< 3.0 × 10^{-6}	CL=90%	2640
$e^+ \nu_e \gamma$		< 4.3 × 10^{-6}	CL=90%	2640
$\mu^+ \nu_\mu \gamma$		< 3.4 × 10^{-6}	CL=90%	2639
$\mu^+ \mu^- \mu^+ \nu_\mu$		< 1.6 × 10^{-8}	CL=95%	2634
Inclusive modes				
$D^0 X$		(8.6 ± 0.7) %		–
$\overline{D}^0 X$		(79 ± 4) %		–
$D^+ X$		(2.5 ± 0.5) %		–
$D^- X$		(9.9 ± 1.2) %		–
$D_s^+ X$		(7.9 $^{+1.4}_{-1.3}$) %		–
$D_s^- X$		(1.10 $^{+0.40}_{-0.32}$) %		–
$\Lambda_c^+ X$		(2.1 $^{+0.9}_{-0.6}$) %		–
$\overline{\Lambda}_c^- X$		(2.8 $^{+1.1}_{-0.9}$) %		–
$\overline{c} X$		(97 ± 4) %		–

B-meson decays

Powerf

- The
  to n
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B^+ DECAY MODES

$\ell^+ \nu_\ell X$
$e^+ \nu_e X_c$
$D \ell^+ \nu_\ell X$
$\overline{D}^0 \ell^+ \nu_\ell$
$\overline{D}^0 \tau^+ \nu_\tau$
$\overline{D}^*(2007)^0 \ell^+ \nu_\ell$
$\overline{D}^*(2007)^0 \tau^+ \nu_\tau$
$D^- \pi^+ \ell^+ \nu_\ell$
$\overline{D}^*_0(2420)^0 \ell^+ \nu_\ell$, $\overline{D}^*_0(2420)^0 \to D^- \pi^+$
$\overline{D}^*_2(2460)^0 \ell^+ \nu_\ell$, $\overline{D}^*_2(2460)^0 \to D^- \pi^+$
$D^{(*)} n \pi \ell^+ \nu_\ell (n \geq$ 1
$D^{*-} \pi^+ \ell^+ \nu_\ell$
$\overline{D}_1(2420)^0 \ell^+ \nu_\ell$, $\overline{D}_1(2420)^0 \to D^{*-} \pi^+$
$\overline{D}'_1(2430)^0 \ell^+ \nu_\ell$, $\overline{D}'_1(2430)^0 \to D^{*-} \pi^+$
$\overline{D}^*_2(2460)^0 \ell^+ \nu_\ell$, $\overline{D}^{*0}_2 \to D^{*}$
$\overline{D}^0 \pi^+ \pi^- \ell^+ \nu_\ell$
$\overline{D}^{*0} \pi^+ \pi^- \ell^+ \nu_\ell$
$D_s^{(*)-} K^+ \ell^+ \nu_\ell$
$D_s^- K^+ \ell^+ \nu_\ell$

HTTP://PDG.LBL.GOV Page 73 Created: 8/28/2020 18:31

$\pi^+ \ell^+ \ell^-$	B1		$< 4.9 \times 10^{-8}$	CL=90%	2638
$\pi^+ e^+ e^-$	B1		$< 8.0 \times 10^{-8}$	CL=90%	2638
$\pi^+ \mu^+ \mu^-$	B1		$(1.75 \pm 0.22) \times 10^{-8}$		2634
$\pi^+ \nu \overline{\nu}$	B1		$< 1.4 \times 10^{-5}$	CL=90%	2638
$K^+ \ell^+ \ell^-$	B1	[lll]	$(4.51 \pm 0.23) \times 10^{-7}$	S=1.1	2617
$K^+ e^+ e^-$	B1		$(5.5 \pm 0.7) \times 10^{-7}$		2617
$K^+ \mu^+ \mu^-$	B1		$(4.41 \pm 0.22) \times 10^{-7}$	S=1.2	2612
$K^+ \mu^+ \mu^-$ nonresonant	B1		$(4.37 \pm 0.27) \times 10^{-7}$		2612
$K^+ \tau^+ \tau^-$	B1		$< 2.25 \times 10^{-3}$	CL=90%	1687
$K^+ \overline{\nu} \nu$	B1		$< 1.6 \times 10^{-5}$	CL=90%	2617
$\rho^+ \nu \overline{\nu}$	B1		$< 3.0 \times 10^{-5}$	CL=90%	2583
$K^*(892)^+ \ell^+ \ell^-$	B1	[lll]	$(1.01 \pm 0.11) \times 10^{-6}$	S=1.1	2564
$K^*(892)^+ e^+ e^-$	B1		$(1.55 ^{+0.40}_{-0.31}) \times 10^{-6}$		2564
$K^*(892)^+ \mu^+ \mu^-$	B1		$(9.6 \pm 1.0) \times 10^{-7}$		2560
$K^*(892)^+ \nu \overline{\nu}$	B1		$< 4.0 \times 10^{-5}$	CL=90%	2564
$K^+ \pi^+ \pi^- \mu^+ \mu^-$	B1		$(4.3 \pm 0.4) \times 10^{-7}$		2593
$\phi K^+ \mu^+ \mu^-$	B1		$(7.9 ^{+2.1}_{-1.7}) \times 10^{-8}$		2490
$\overline{\Lambda} p \nu \overline{\nu}$			$< 3.0 \times 10^{-5}$	CL=90%	2430
$\pi^+ e^+ \mu^-$	LF		$< 6.4 \times 10^{-3}$	CL=90%	2637
$\pi^+ e^- \mu^+$	LF		$< 6.4 \times 10^{-3}$	CL=90%	2637
$\pi^+ e^\pm \mu^\mp$	LF		$< 1.7 \times 10^{-7}$	CL=90%	2637
$\pi^+ e^+ \tau^-$	LF		$< 7.4 \times 10^{-5}$	CL=90%	2338
$\pi^+ e^- \tau^+$	LF		$< 2.0 \times 10^{-5}$	CL=90%	2338
$\pi^+ e^\pm \tau^\mp$	LF		$< 7.5 \times 10^{-5}$	CL=90%	2338
$\pi^+ \mu^+ \tau^-$	LF		$< 6.2 \times 10^{-5}$	CL=90%	2333
$\pi^+ \mu^- \tau^+$	LF		$< 4.5 \times 10^{-5}$	CL=90%	2333
$\pi^+ \mu^\pm \tau^\mp$	LF		$< 7.2 \times 10^{-5}$	CL=90%	2333
$K^+ e^+ \mu^-$	LF		$< 7.0 \times 10^{-9}$	CL=90%	2615
$K^+ e^- \mu^+$	LF		$< 6.4 \times 10^{-9}$	CL=90%	2615

$D_s^{*-} K^+ \ell^+ \nu_\ell$	$(2.9 \pm 1.9) \times 10^{-4}$		2185
$\pi^0 \ell^+ \nu_\ell$	$(7.80 \pm 0.27) \times 10^{-5}$		2638
$\eta \ell^+ \nu_\ell$	$(3.9 \pm 0.5) \times 10^{-5}$		2611
	$(2.3 \pm 0.8) \times 10^{-5}$		2553
	$(1.19 \pm 0.09) \times 10^{-4}$		2582
	$(1.58 \pm 0.11) \times 10^{-4}$		2583
	$(5.8 ^{+2.6}_{-2.3}) \times 10^{-6}$		2467
	8.5×10^{-6}	CL=90%	2446
	$(8.2 ^{+4.0}_{-3.3}) \times 10^{-6}$		2467
	9.8×10^{-7}	CL=90%	2640
	90×10^{-07} to 1.07×10^{-06}	CL=90%	2639
	$(1.09 \pm 0.24) \times 10^{-4}$	S=1.2	2341
	3.0×10^{-6}	CL=90%	2640
	4.3×10^{-6}	CL=90%	2640
	3.4×10^{-6}	CL=90%	2639
	1.6×10^{-8}	CL=95%	2634

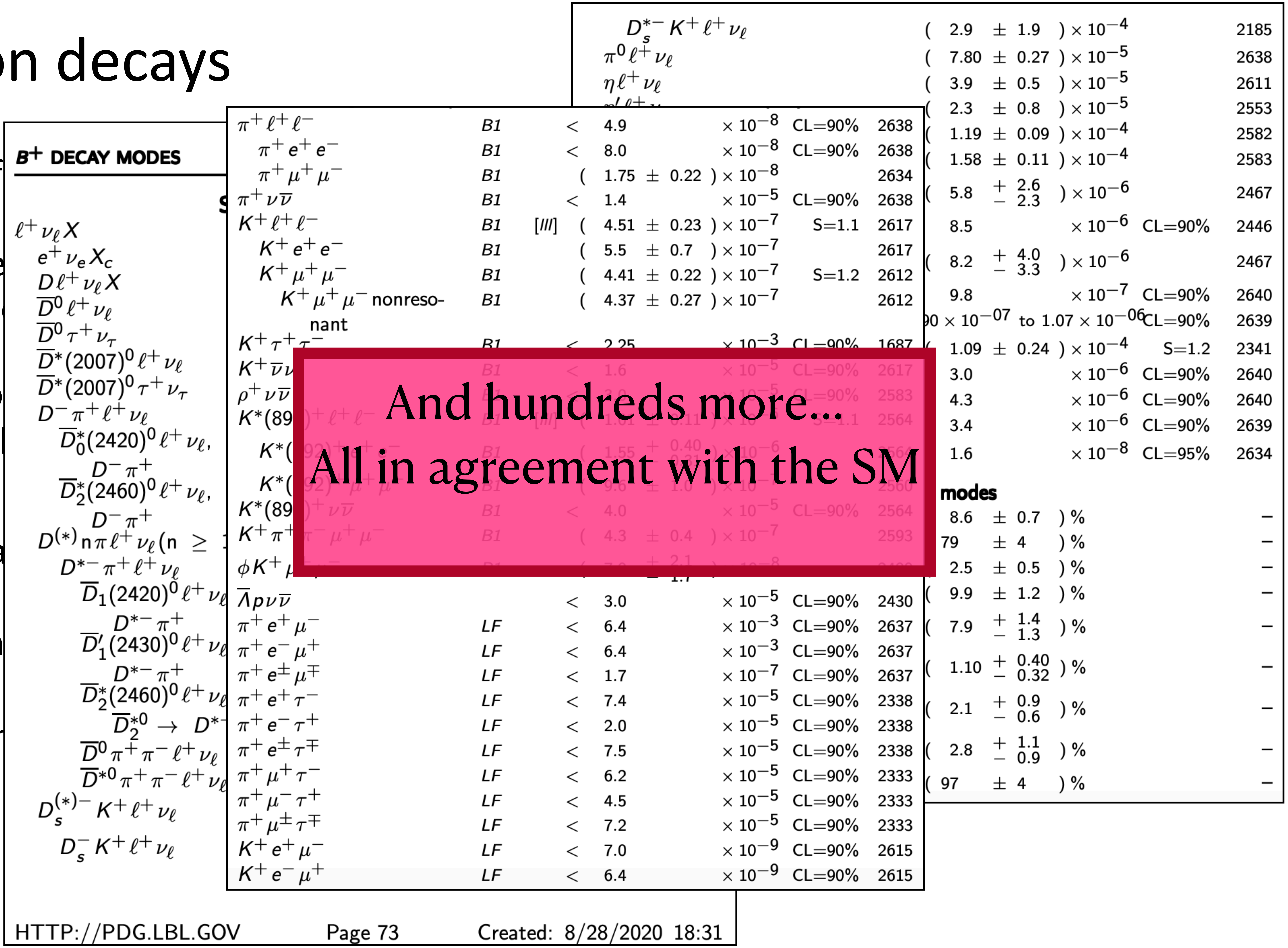
e modes

	(8.6 ± 0.7) %	–
	(79 ± 4) %	–
	(2.5 ± 0.5) %	–
	(9.9 ± 1.2) %	–
	$(7.9 ^{+1.4}_{-1.3})$ %	–
	$(1.10 ^{+0.40}_{-0.32})$ %	–
	$(2.1 ^{+0.9}_{-0.6})$ %	–
	$(2.8 ^{+1.1}_{-0.9})$ %	–
	(97 ± 4) %	–

B-meson decays

Powerf…

- The…
  to n…
- Exp…
  LHC…
- Cha…
- Lon…
- Hur…



B^+ DECAY MODES

- $\ell^+ \nu_\ell X$
- $e^+ \nu_e X_c$
- $D \ell^+ \nu_\ell X$
- $\overline{D}^0 \ell^+ \nu_\ell$
- $\overline{D}^0 \tau^+ \nu_\tau$
- $\overline{D}^*(2007)^0 \ell^+ \nu_\ell$
- $\overline{D}^*(2007)^0 \tau^+ \nu_\tau$
- $D^- \pi^+ \ell^+ \nu_\ell$
- $\overline{D}_0^*(2420)^0 \ell^+ \nu_\ell$, $\overline{D}_0^{*0} \to D^- \pi^+$
- $\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell$, $\overline{D}_2^{*0} \to D^- \pi^+$
- $D^{(*)} n\pi \ell^+ \nu_\ell (n \geq$ …
- $D^{*-} \pi^+ \ell^+ \nu_\ell$
- $\overline{D}_1(2420)^0 \ell^+ \nu_\ell$ … $D^{*-}\pi^+$
- $\overline{D}'_1(2430)^0 \ell^+ \nu_\ell$ … $D^{*-}\pi^+$
- $\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell$ … $\overline{D}_2^{*0} \to D^{*}$…
- $\overline{D}^0 \pi^+ \pi^- \ell^+ \nu_\ell$
- $\overline{D}^{*0} \pi^+ \pi^- \ell^+ \nu_\ell$
- $D_s^{(*)-} K^+ \ell^+ \nu_\ell$
- $D_s^- K^+ \ell^+ \nu_\ell$

$\pi^+ \ell^+ \ell^-$	B1	< 4.9	$\times 10^{-8}$	CL=90%	2638
$\pi^+ e^+ e^-$	B1	< 8.0	$\times 10^{-8}$	CL=90%	2638
$\pi^+ \mu^+ \mu^-$	B1	(1.75 ± 0.22)	$\times 10^{-8}$		2634
$\pi^+ \nu \overline{\nu}$	B1	< 1.4	$\times 10^{-5}$	CL=90%	2638
$K^+ \ell^+ \ell^-$	B1 [lll]	(4.51 ± 0.23)	$\times 10^{-7}$	S=1.1	2617
$K^+ e^+ e^-$	B1	(5.5 ± 0.7)	$\times 10^{-7}$		2617
$K^+ \mu^+ \mu^-$	B1	(4.41 ± 0.22)	$\times 10^{-7}$	S=1.2	2612
$K^+ \mu^+ \mu^-$ nonresonant	B1	(4.37 ± 0.27)	$\times 10^{-7}$		2612
$\overline{\Lambda} p \nu \overline{\nu}$		< 3.0	$\times 10^{-5}$	CL=90%	2430
$\pi^+ e^+ \mu^-$	LF	< 6.4	$\times 10^{-3}$	CL=90%	2637
$\pi^+ e^- \mu^+$	LF	< 6.4	$\times 10^{-3}$	CL=90%	2637
$\pi^+ e^\pm \mu^\mp$	LF	< 1.7	$\times 10^{-7}$	CL=90%	2637
$\pi^+ e^+ \tau^-$	LF	< 7.4	$\times 10^{-5}$	CL=90%	2338
$\pi^+ e^- \tau^+$	LF	< 2.0	$\times 10^{-5}$	CL=90%	2338
$\pi^+ e^\pm \tau^\mp$	LF	< 7.5	$\times 10^{-5}$	CL=90%	2338
$\pi^+ \mu^+ \tau^-$	LF	< 6.2	$\times 10^{-5}$	CL=90%	2333
$\pi^+ \mu^- \tau^+$	LF	< 4.5	$\times 10^{-5}$	CL=90%	2333
$\pi^+ \mu^\pm \tau^\mp$	LF	< 7.2	$\times 10^{-5}$	CL=90%	2333
$K^+ e^+ \mu^-$	LF	< 7.0	$\times 10^{-9}$	CL=90%	2615
$K^+ e^- \mu^+$	LF	< 6.4	$\times 10^{-9}$	CL=90%	2615

$D_s^{*-} K^+ \ell^+ \nu_\ell$	$(2.9 \pm 1.9) \times 10^{-4}$			2185
$\pi^0 \ell^+ \nu_\ell$	$(7.80 \pm 0.27) \times 10^{-5}$			2638
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	9.8×10^{-7}	CL=90%		2640
	…90 $\times 10^{-07}$ to 1.07×10^{-06}	CL=90%		2639
	$(1.09 \pm 0.24) \times 10^{-4}$	S=1.2		2341
	3.0×10^{-6}	CL=90%		2640
	4.3×10^{-6}	CL=90%		2640
	3.4×10^{-6}	CL=90%		2639
	1.6×10^{-8}	CL=95%		2634
modes				
	(8.6 ± 0.7) %			–
	(79 ± 4) %			–
	(2.5 ± 0.5) %			–
	(9.9 ± 1.2) %			–
	$(7.9 {}^{+1.4}_{-1.3})$ %			–
	$(1.10 {}^{+0.40}_{-0.32})$ %			–
	$(2.1 {}^{+0.9}_{-0.6})$ %			–
	$(2.8 {}^{+1.1}_{-0.9})$ %			–
	(97 ± 4) %			–

HTTP://PDG.LBL.GOV Page 73 Created: 8/28/2020 18:31

And hundreds more…
All in agreement with the SM

B-meson decays

Powerf…

- The … to n…
- Exp… LHC…
- Cha…
- Lon…
- Hur…

B^+ DECAY MODES

$\ell^+ \nu_\ell X$
$e^+ \nu_e X_c$
$D \ell^+ \nu_\ell X$
$\overline{D}^0 \ell^+ \nu_\ell$
$\overline{D}^0 \tau^+ \nu_\tau$
$\overline{D}^*(2007)^0 \ell^+ \nu_\ell$
$\overline{D}^*(2007)^0 \tau^+ \nu_\tau$
$D^- \pi^+ \ell^+ \nu_\ell$
$\overline{D}_0^*(2420)^0 \ell^+ \nu_\ell$, $D^- \pi^+$
$\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell$, $D^- \pi^+$
$D^{(*)} n\pi \ell^+ \nu_\ell (n \geq 1)$
$D^{*-} \pi^+ \ell^+ \nu_\ell$
$\overline{D}_1(2420)^0 \ell^+ \nu_\ell$, $D^{*-} \pi^+$
$\overline{D}_1'(2430)^0 \ell^+ \nu_\ell$, $D^{*-} \pi^+$
$\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell$, $\overline{D}_2^{*0} \to D^{*-}$…
$\overline{D}^0 \pi^+ \pi^- \ell^+ \nu_\ell$
$\overline{D}^{*0} \pi^+ \pi^- \ell^+ \nu_\ell$
$D_s^{(*)-} K^+ \ell^+ \nu_\ell$
$D_s^- K^+ \ell^+ \nu_\ell$

$\pi^+ \ell^+ \ell^-$	B1	$< 4.9 \times 10^{-8}$	CL=90%	2638
$\pi^+ e^+ e^-$	B1	$< 8.0 \times 10^{-8}$	CL=90%	2638
$\pi^+ \mu^+ \mu^-$	B1	$(1.75 \pm 0.22) \times 10^{-8}$		2634
$\pi^+ \nu \overline{\nu}$	B1	$< 1.4 \times 10^{-5}$	CL=90%	2638
$K^+ \ell^+ \ell^-$	B1 [lll]	$(4.51 \pm 0.23) \times 10^{-7}$	S=1.1	2617
$K^+ e^+ e^-$	B1	$(5.5 \pm 0.7) \times 10^{-7}$		2617
$K^+ \mu^+ \mu^-$	B1	$(4.41 \pm 0.22) \times 10^{-7}$	S=1.2	2612
$K^+ \mu^+ \mu^-$ nonresonant	B1	$(4.37 \pm 0.27) \times 10^{-7}$		2612
$K^+ \nu \overline{\nu}$	B1	$< 1.6 \times 10^{-5}$	CL=90%	2617
$K^*(892)^+ \ell^+ \ell^-$	B1 [lll]	$(1.01 \pm 0.11) \times 10^{-6}$	S=1.1	2564
$K^*(892)^+ e^+ e^-$	B1	$(1.55 \ldots) \times 10^{-6}$		2564
$K^*(892)^+ \mu^+ \mu^-$	B1	$(9.6 \pm 1.0) \times 10^{-7}$		2560
$K^*(892)^+ \nu \overline{\nu}$	B1	$< 4.0 \times 10^{-5}$	CL=90%	2564
$K^+ \pi^+ \pi^- \mu^+ \mu^-$	B1	$(4.3 \pm 0.4) \times 10^{-7}$		2593
$\overline{\Lambda} p \nu \overline{\nu}$		$< 3.0 \times 10^{-5}$	CL=90%	2430
$\pi^+ e^+ \mu^-$	LF	$< 6.4 \times 10^{-3}$	CL=90%	2637
$\pi^+ e^- \mu^+$	LF	$< 6.4 \times 10^{-3}$	CL=90%	2637
$\pi^+ e^\pm \mu^\mp$	LF	$< 1.7 \times 10^{-7}$	CL=90%	2637
$\pi^+ e^+ \tau^-$	LF	$< 7.4 \times 10^{-5}$	CL=90%	2338
$\pi^+ e^- \tau^+$	LF	$< 2.0 \times 10^{-5}$	CL=90%	2338
$\pi^+ e^\pm \tau^\mp$	LF	$< 7.5 \times 10^{-5}$	CL=90%	2338
$\pi^+ \mu^+ \tau^-$	LF	$< 6.2 \times 10^{-5}$	CL=90%	2333
$\pi^+ \mu^- \tau^+$	LF	$< 4.5 \times 10^{-5}$	CL=90%	2333
$\pi^+ \mu^\pm \tau^\mp$	LF	$< 7.2 \times 10^{-5}$	CL=90%	2333
$K^+ e^+ \mu^-$	LF	$< 7.0 \times 10^{-9}$	CL=90%	2615
$K^+ e^- \mu^+$	LF	$< 6.4 \times 10^{-9}$	CL=90%	2615

$D_s^{*-} K^+ \ell^+ \nu_\ell$	$(2.9 \pm 1.9) \times 10^{-4}$		2185
$\pi^0 \ell^+ \nu_\ell$	$(7.80 \pm 0.27) \times 10^{-5}$		2638
$\eta \ell^+ \nu_\ell$	$(3.9 \pm 0.5) \times 10^{-5}$		2611
	$(2.3 \pm 0.8) \times 10^{-5}$		2553
	$(1.19 \pm 0.09) \times 10^{-4}$		2582
	$(1.58 \pm 0.11) \times 10^{-4}$		2583
	$(5.8 {}^{+2.6}_{-2.3}) \times 10^{-6}$		2467
	8.5×10^{-6}	CL=90%	2446
	$(8.2 {}^{+4.0}_{-3.3}) \times 10^{-6}$		2467
	9.8×10^{-7}	CL=90%	2640
	…90 $\times 10^{-07}$ to 1.07×10^{-06}	CL=90%	2639
	$(\ldots \pm 0.24) \times 10^{-4}$	S=1.2	2341
	$\times 10^{-6}$	CL=90%	2640
	$\times 10^{-6}$	CL=90%	2640
	3.4×10^{-6}	CL=90%	2639
	1.6×10^{-8}	CL=95%	2634
	(8.6 ± 0.7) %		–
	(79 ± 4) %		–
	$(\ldots \pm 0.5)$ %		–
	(9.9 ± 1.2) %		–
	$(7.9 {}^{+1.4}_{-1.3})$ %		–
	$(1.10 {}^{+0.40}_{-0.32})$ %		–
	$(2.1 {}^{+0.9}_{-0.6})$ %		–
	$(2.8 {}^{+1.1}_{-0.9})$ %		–
	(97 ± 4) %		–

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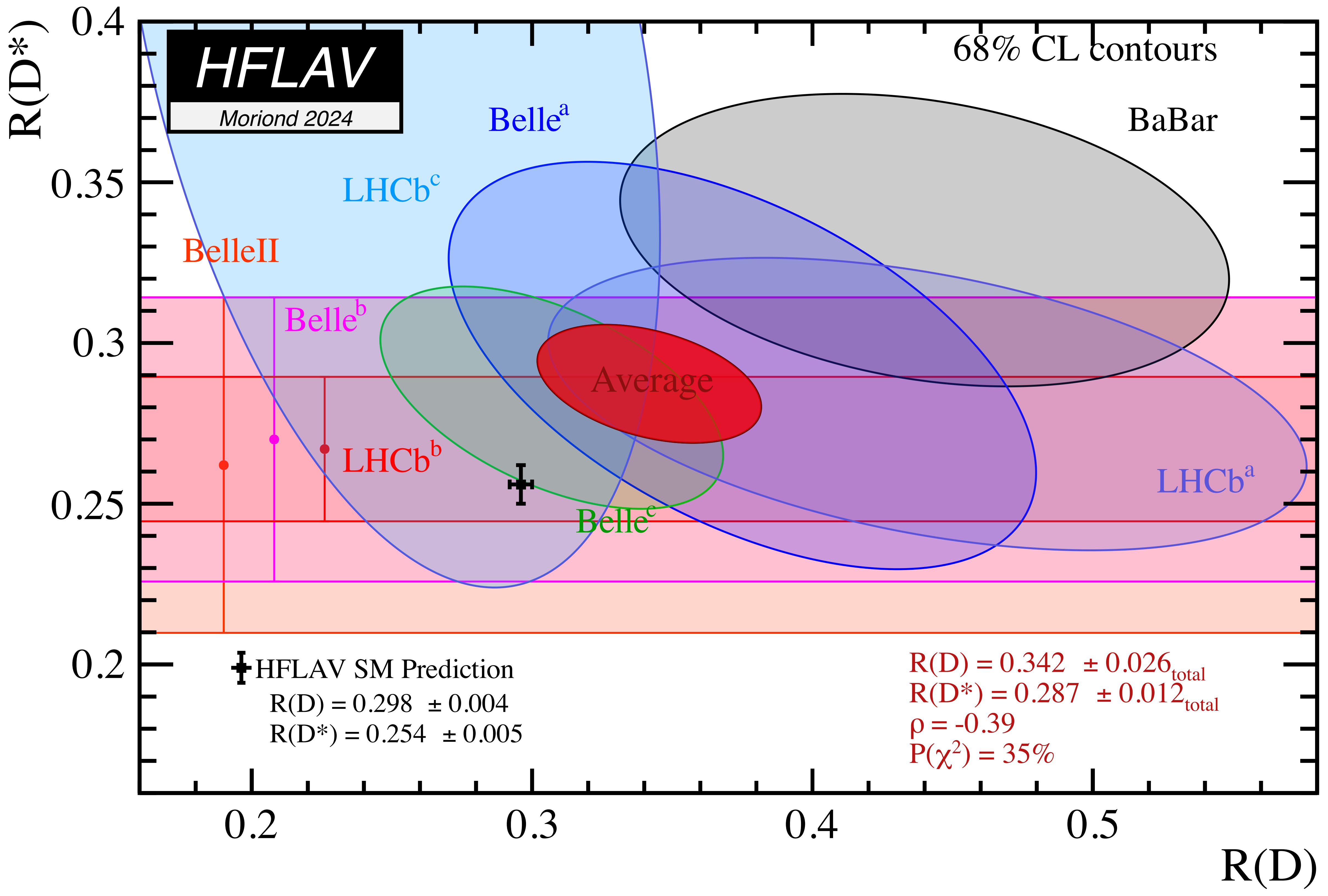
But: Significant deviation from SM observed in $B \to D^{(*)} \ell \nu$ decays

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?

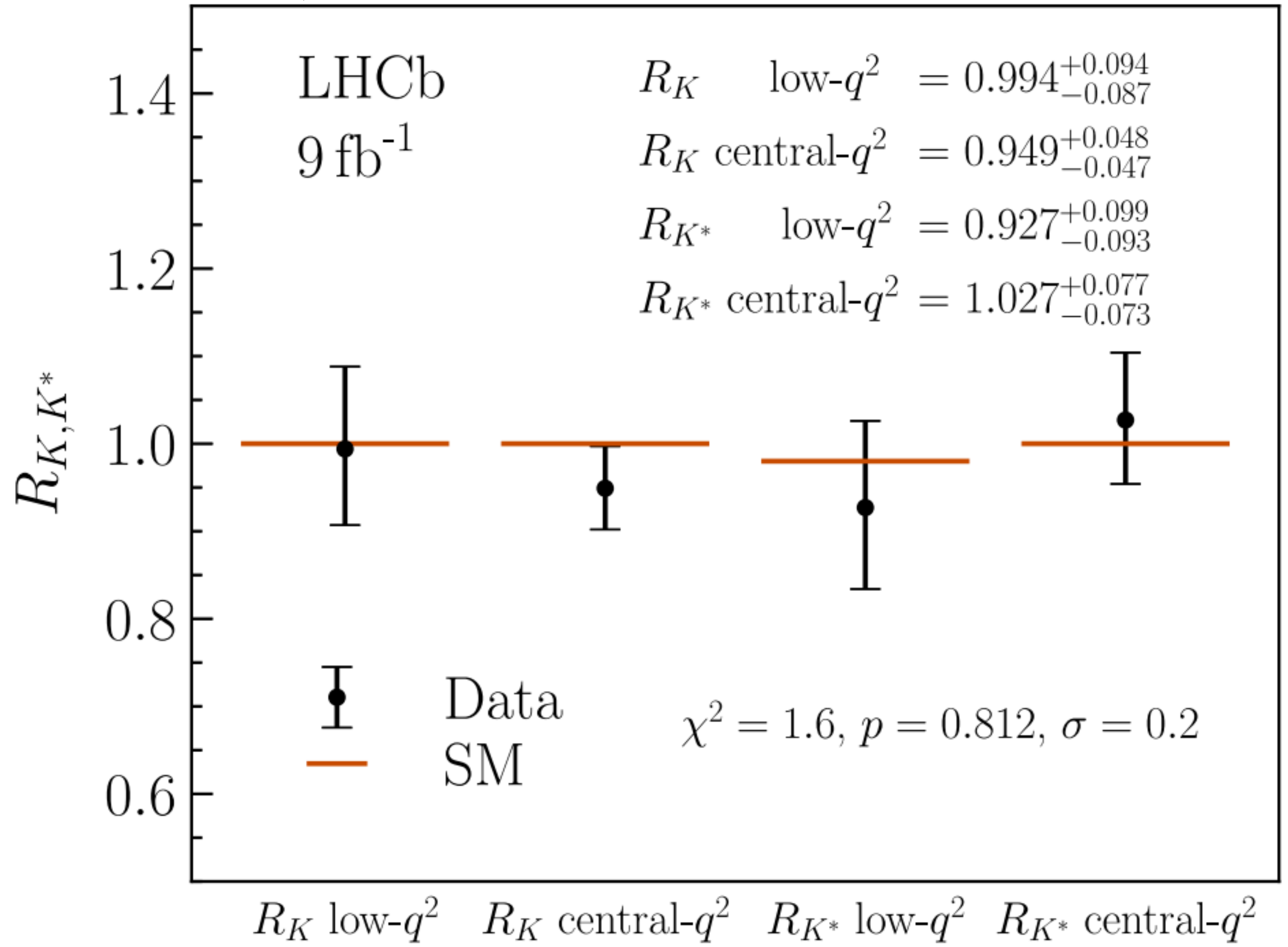
Observables in $b \to s\ell\ell$

$$R_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)}\mu\mu)}{\Gamma(B \to K^{(*)}ee)}$$

- (Another) test of lepton flavour universality
- Theoretically very clean 1810.08132 1605.07633
- **Combined deviation from the SM** $\sim 4\,\sigma$**,** until December 2022.

(now fully consistent with the SM)

2212.09153



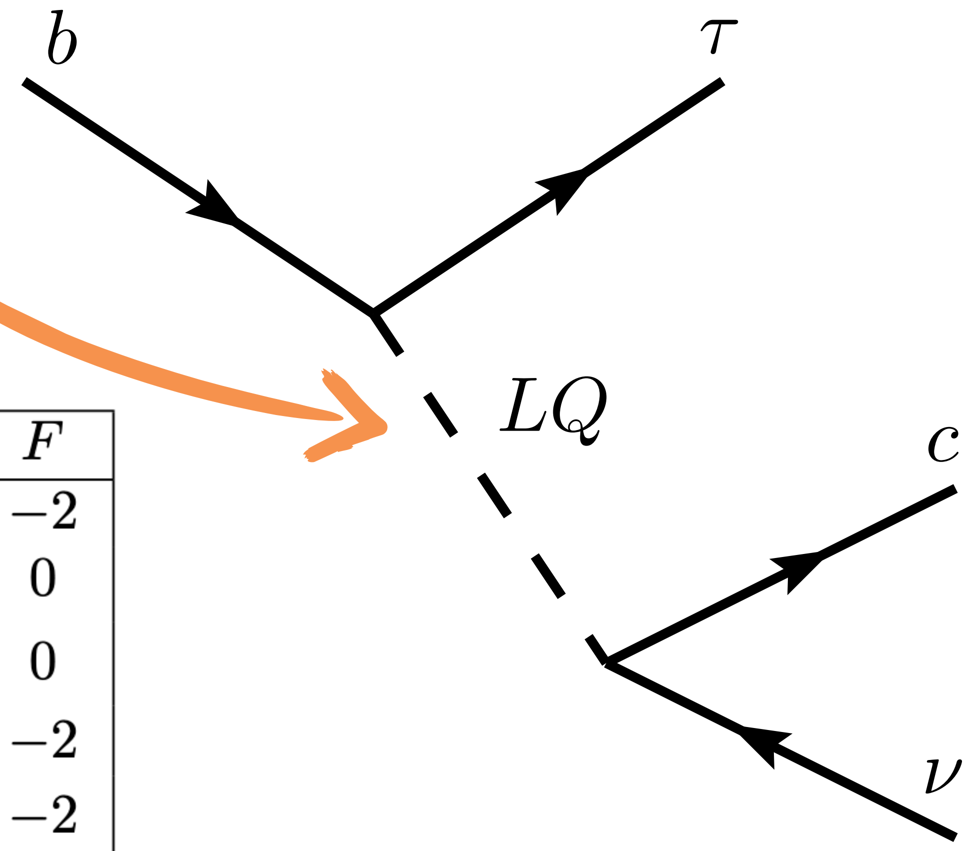
SM prediction	0.9936	1.0007	0.9832	0.9964
SM uncertainty	0.0003	0.0003	0.0014	0.0006
QED uncertainty	0.01	0.01	0.01	0.01

Possible explanations of $R_{D^{(*)}}$

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

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

- 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
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$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	0	S_1	$LL\,(S_0^L),\ RR\,(S_0^R),\ \overline{RR}\,(S_0^{\overline{R}})$	-2
$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	0	$\bar{S}_1$	$\overline{RR}\,(\bar{S}_0^{\overline{R}})$	-2
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(1603.04993)

Possible explanations of $R_{D^{(*)}}$

$$\mathcal{L}_{b\to c\tau\nu} = -2\sqrt{2}G_F V_{cb}\Big[(1+g_{V_L})\,(\bar{c}_L\gamma^\mu b_L)\,(\bar{\tau}_L\gamma_\mu\nu_{\tau L}) + g_{V_R}\,(\bar{c}_R\gamma^\mu b_R)\,(\bar{\tau}_L\gamma_\mu\nu_{\tau L})$$
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$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	0	$\tilde{S}_1$	$RR\,(\tilde{S}_0^R)$	-2
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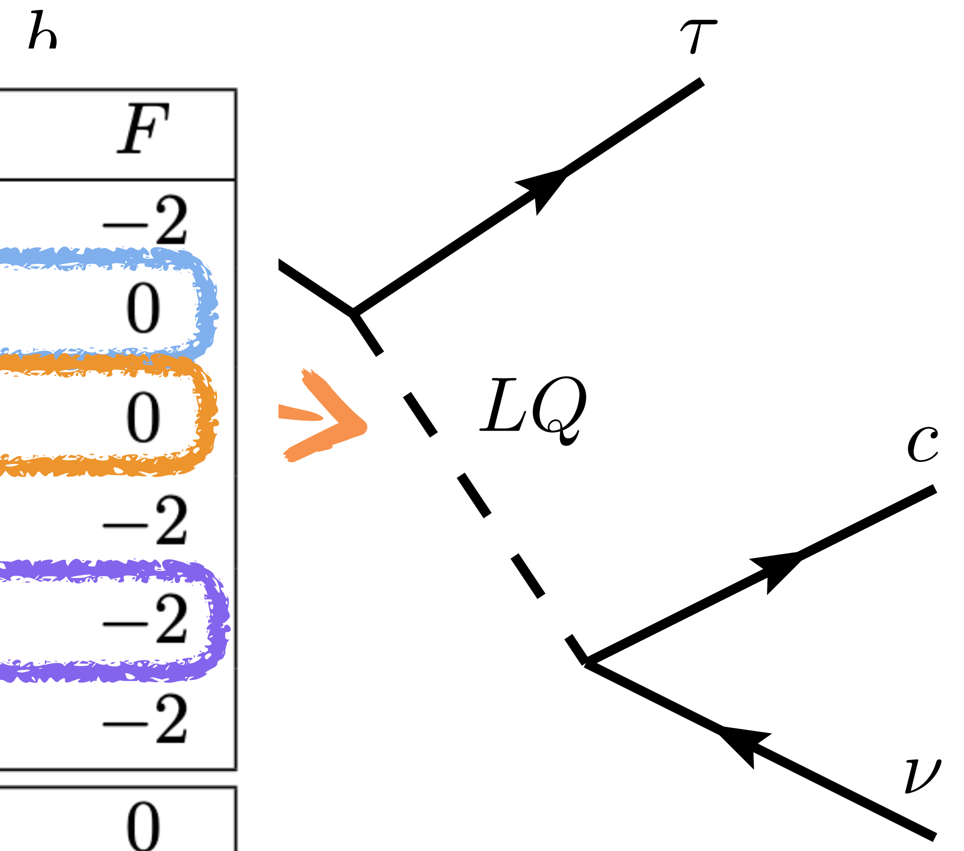
(1603.04993)



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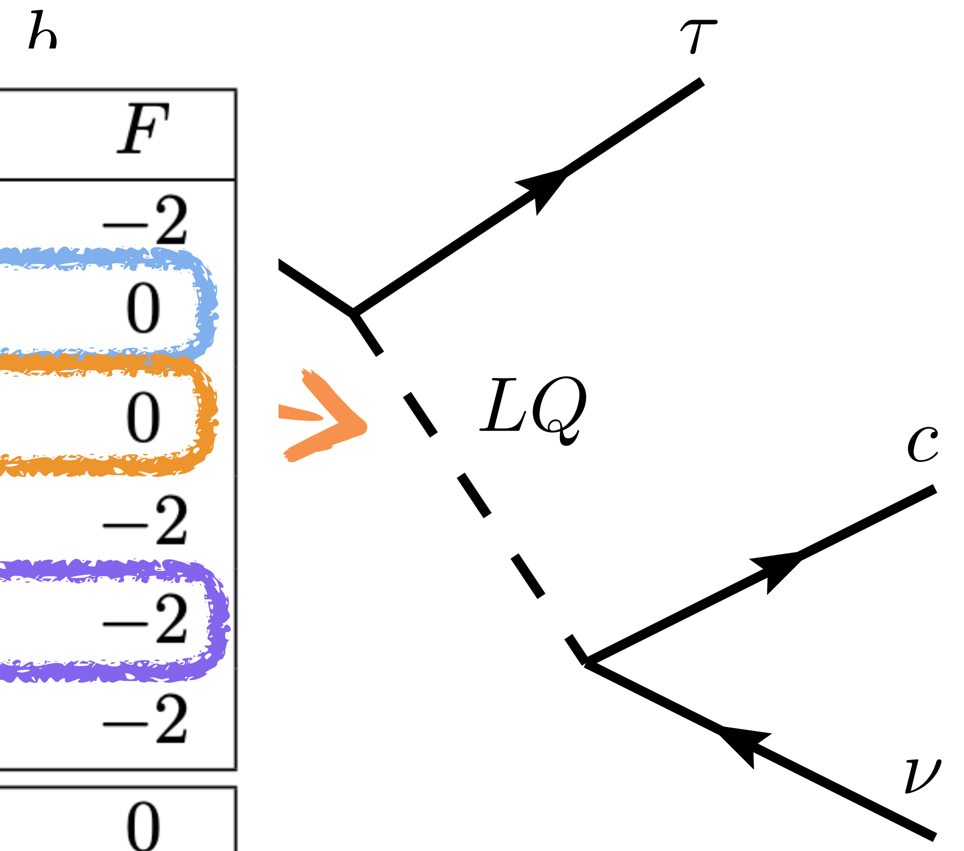

1706.07808
1712.01368
2405.06062

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$(\mathbf{3}, \mathbf{2}, 1/6)$	0	$\tilde{R}_2$	$RL\,(\tilde{S}_{1/2}^L),\ \overline{LR}\,(\tilde{S}_{1/2}^L)$	0
$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	0	$\tilde{S}_1$	$RR\,(\tilde{S}_0^R)$	-2
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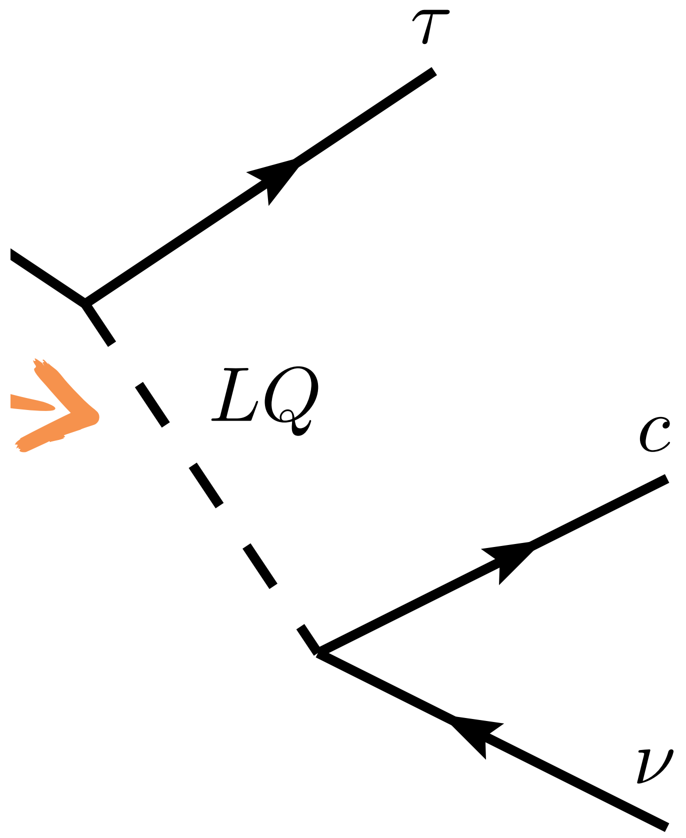


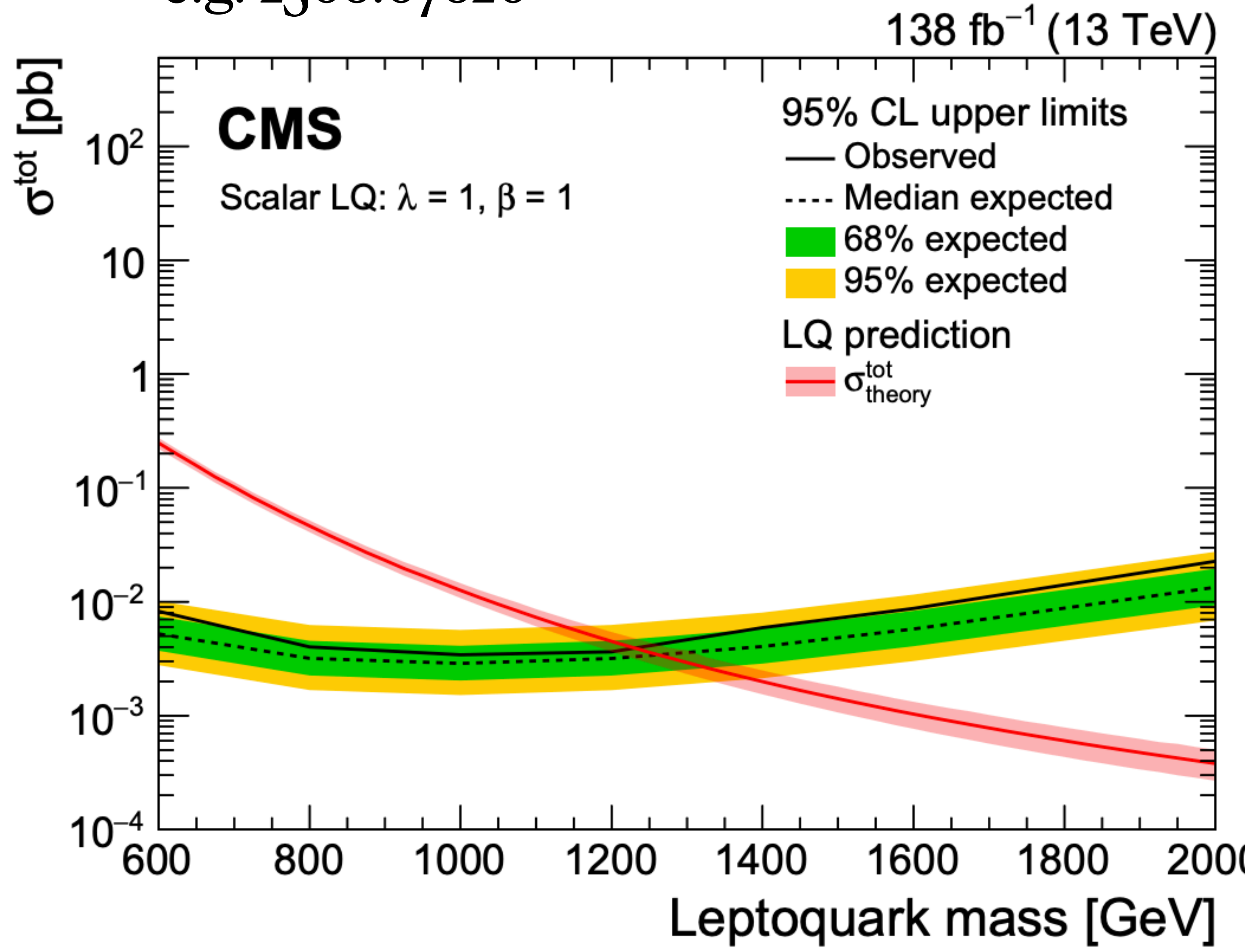
(1603.04993)

Constraints on LQ models - collider bounds

- Direct searches ⇒ $M_{LQ}^{\text{min}} \sim 1\ \text{TeV} - 1.5\ \text{TeV}$

2101.11582
2401.11928 } ATLAS
2308.07826 — CMS

e.g. 2308.07826



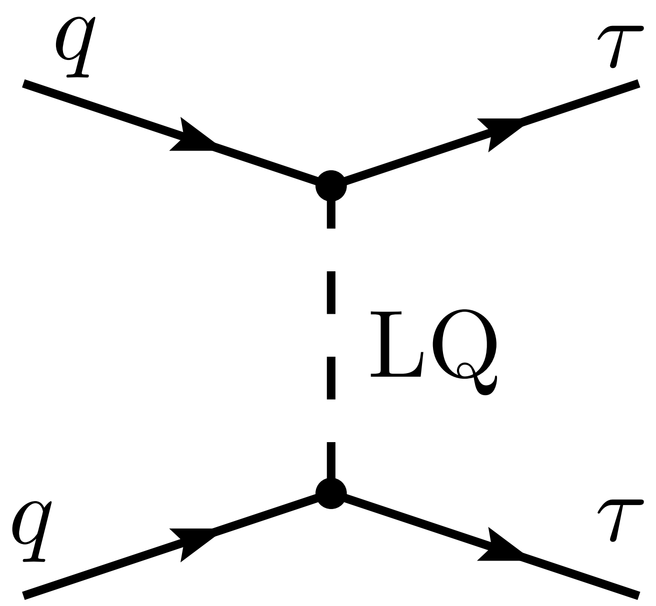
- **High-p_T** tails in $pp \to \tau\tau$, $pp \to \tau\nu$

⇒ Mathematica package High-pT

HighPT

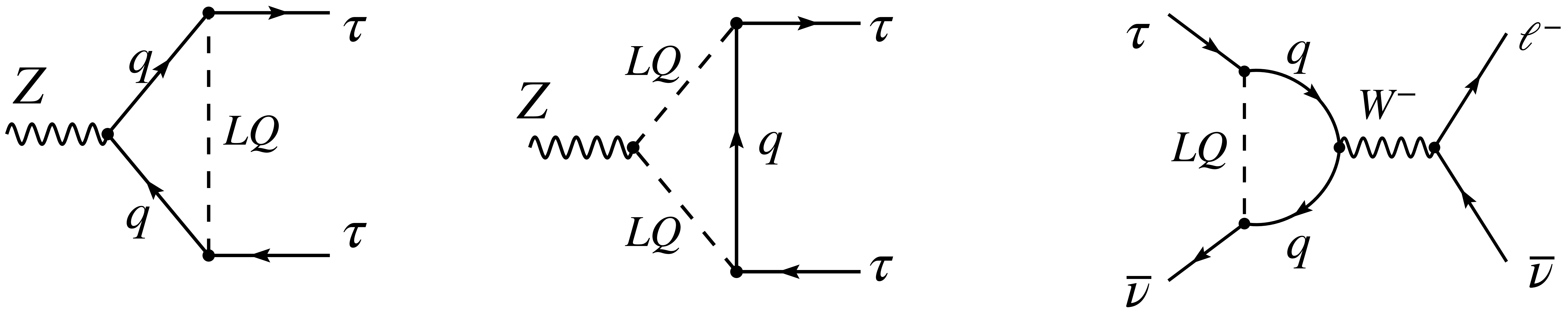
2207.10756
2207.10714
2112.14604
1801.07641

e.g.



Constraints on LQ models - electroweak and flavour

- **Electroweak precision observables:** $Z \to \tau\tau, Z \to \nu\nu, \tau \to \ell\nu\bar{\nu}$ 1901.06315



- 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

- Correlations between flavour observables are highly model dependent

  ⇒ i.e. dependent on the quantum numbers and “texture” of couplings

$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$

- Consider minimal coupling texture

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

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

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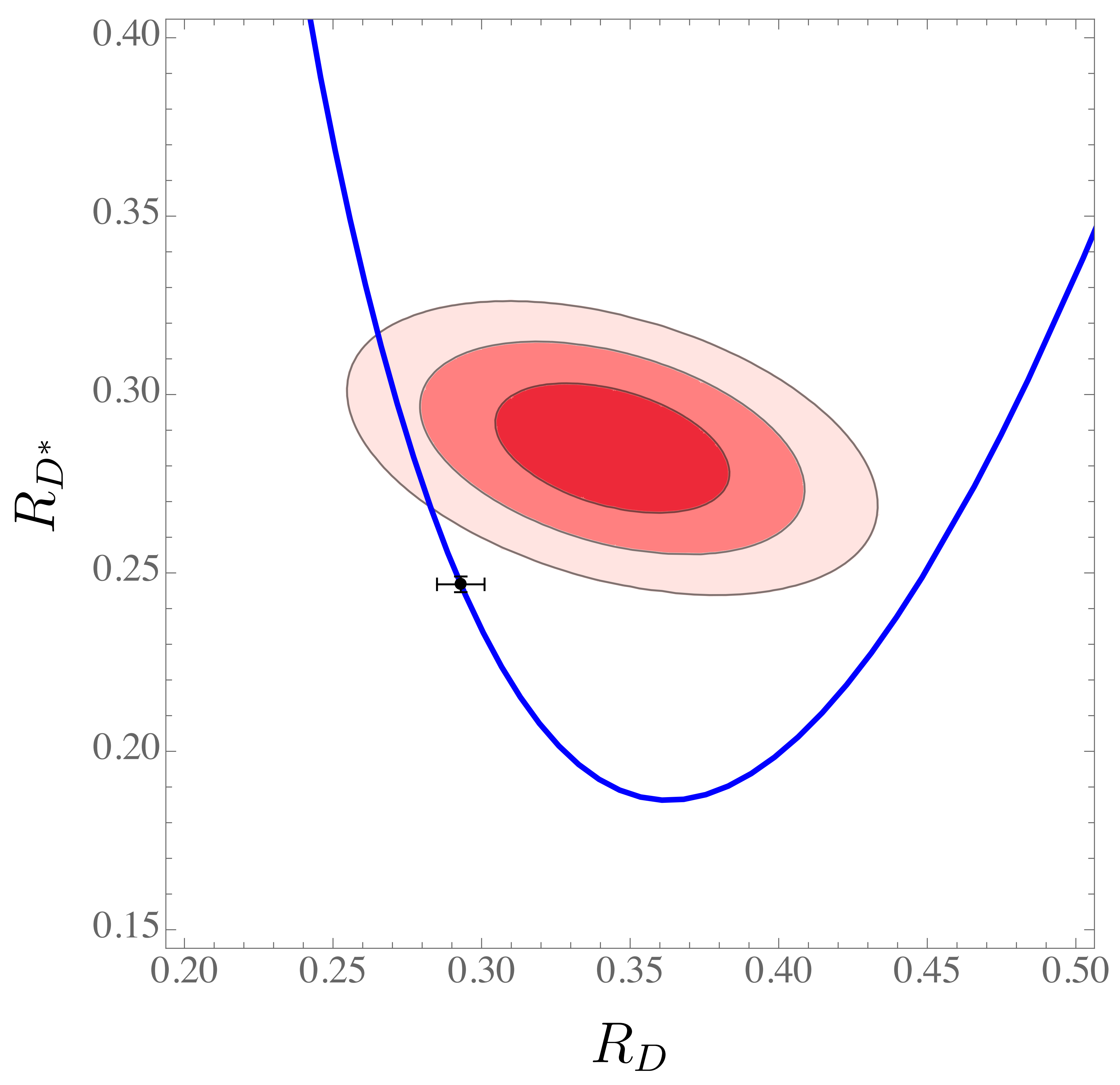
$$\frac{R_D}{R_D^{\text{SM}}} = 1 + 11.1\,\text{Re}(g_S) + 65.4|g_S|^2$$

$$\frac{R_{D^*}}{R_{D^*}^{\text{SM}}} = 1 - 25.5\,\text{Re}(g_S) + 663|g_S|^2$$

$$g_S = -0.59\,\frac{y_R^{b\tau}\, y_L^{b\tau *}}{2}$$

After matching and running...

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



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

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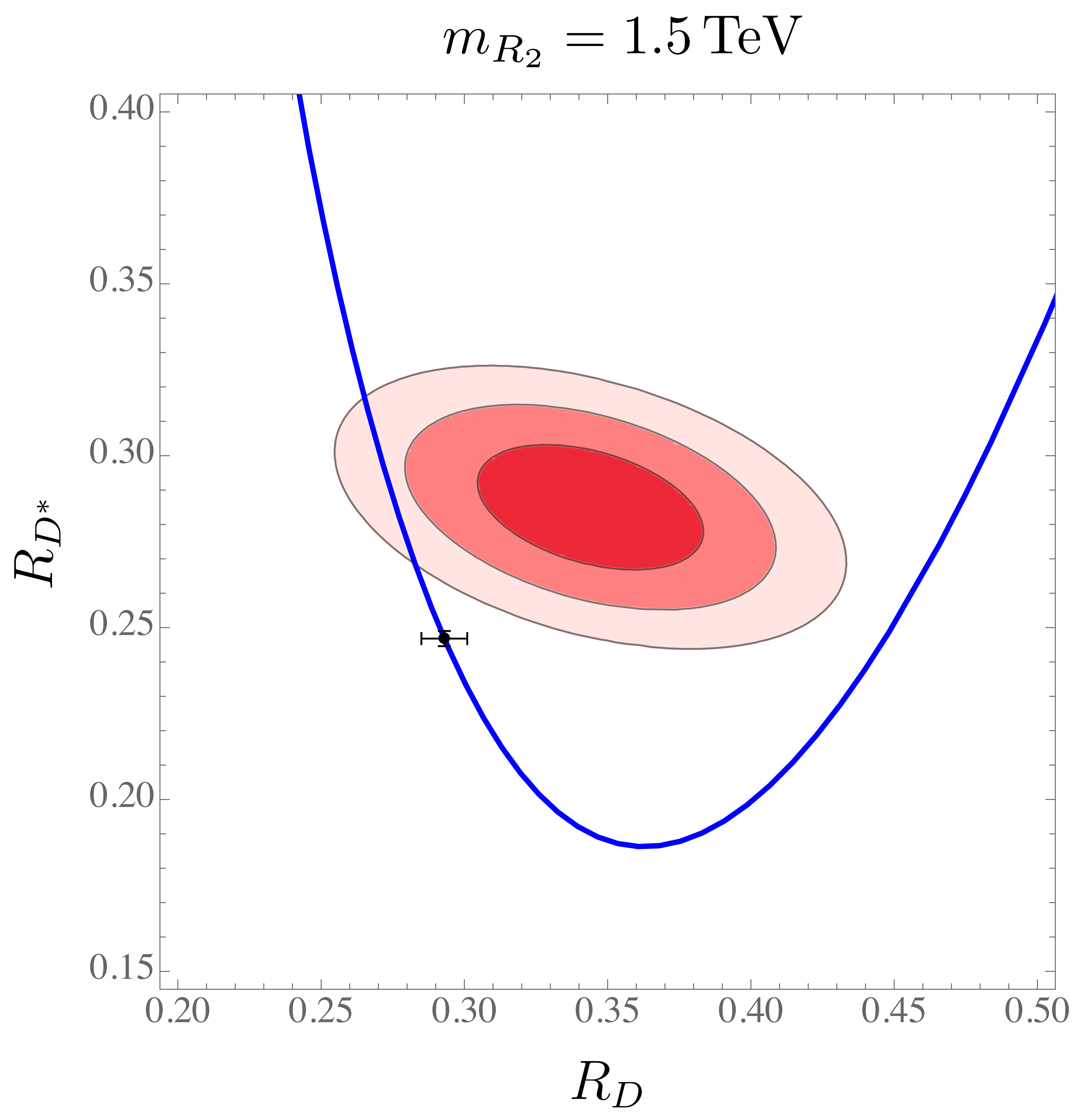
- **Fails to accommodate for the anomaly … Unless?**



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- Consider minimal coupling texture

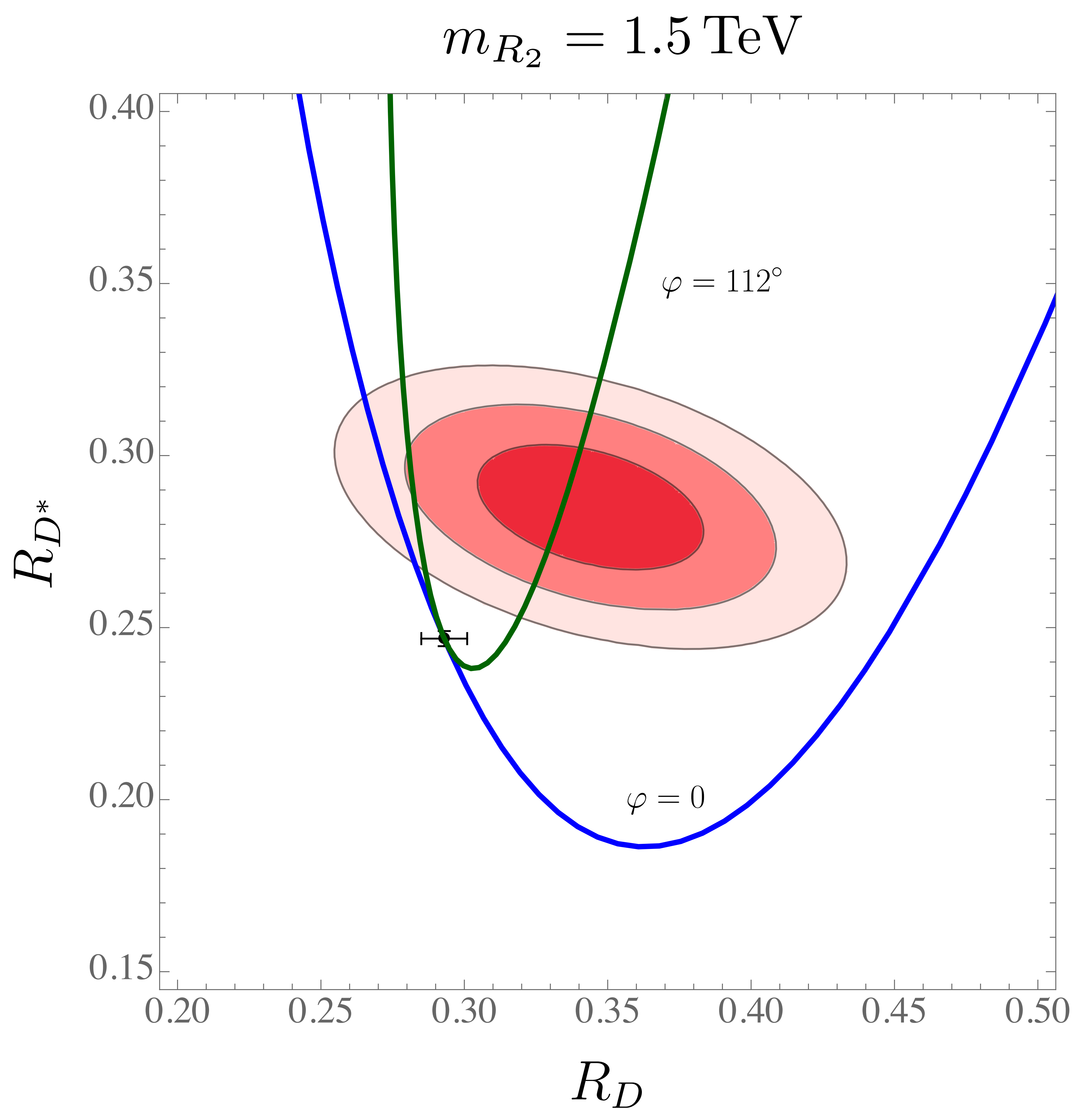
$$y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix}, \qquad y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

$$\frac{R_D}{R_D^{\rm SM}} = 1 + 11.1\,\text{Re}(g_S\, e^{-i\varphi}) + 65.4|g_S\, e^{-i\varphi}|^2$$

$$\frac{R_{D^*}}{R_{D^*}^{\rm SM}} = 1 - 25.5\,\text{Re}(g_S\, e^{-i\varphi}) + 663|g_S\, e^{-i\varphi}|^2$$

- Fails to accommodate for the anomaly... Unless? ⇒ **We allow couplings to have imaginary part!**

1309.0301 2002.07272
1806.05689 2206.09717



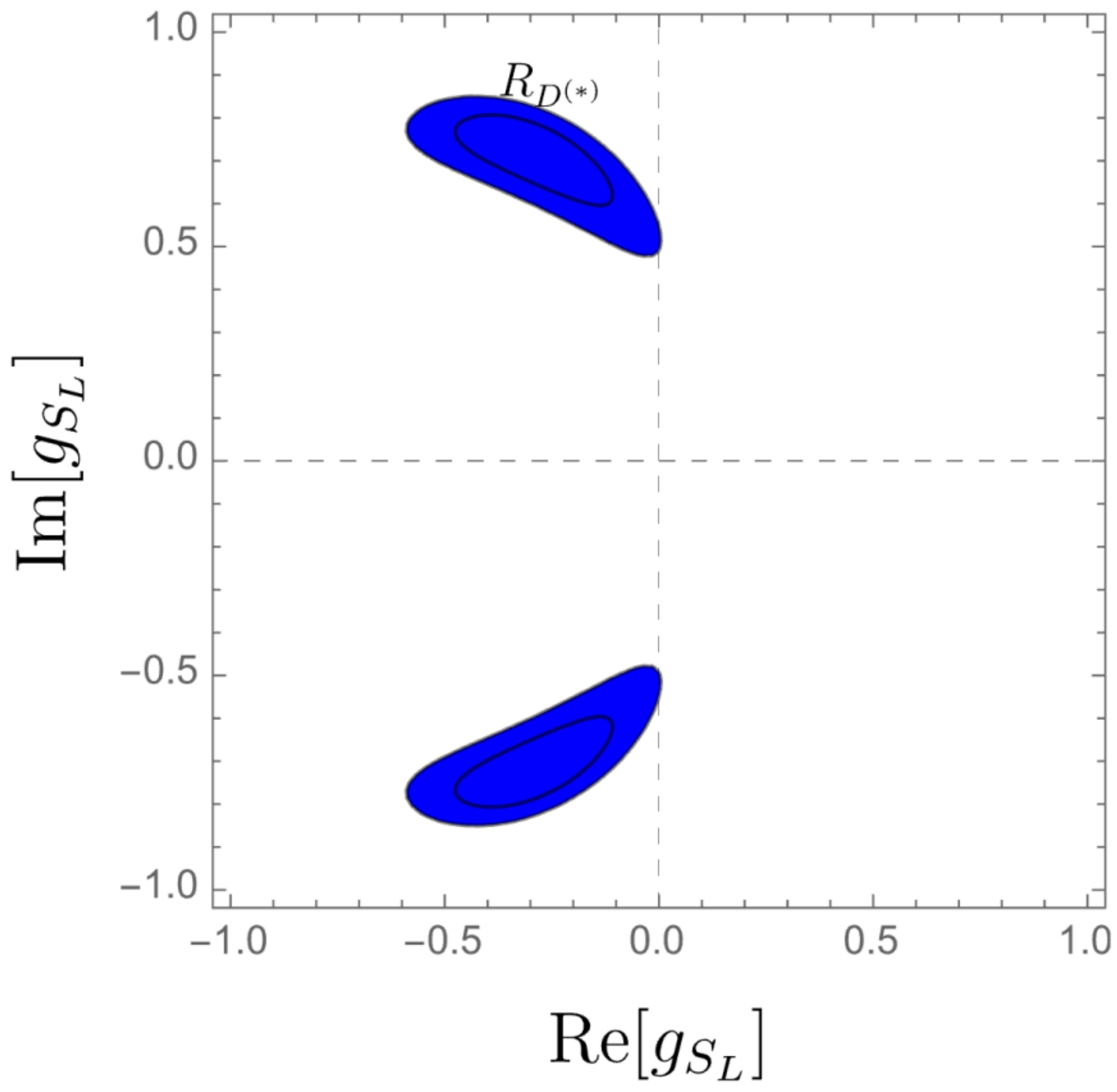
$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$

- Consider minimal coupling texture

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

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

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



*2σ allowed regions

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

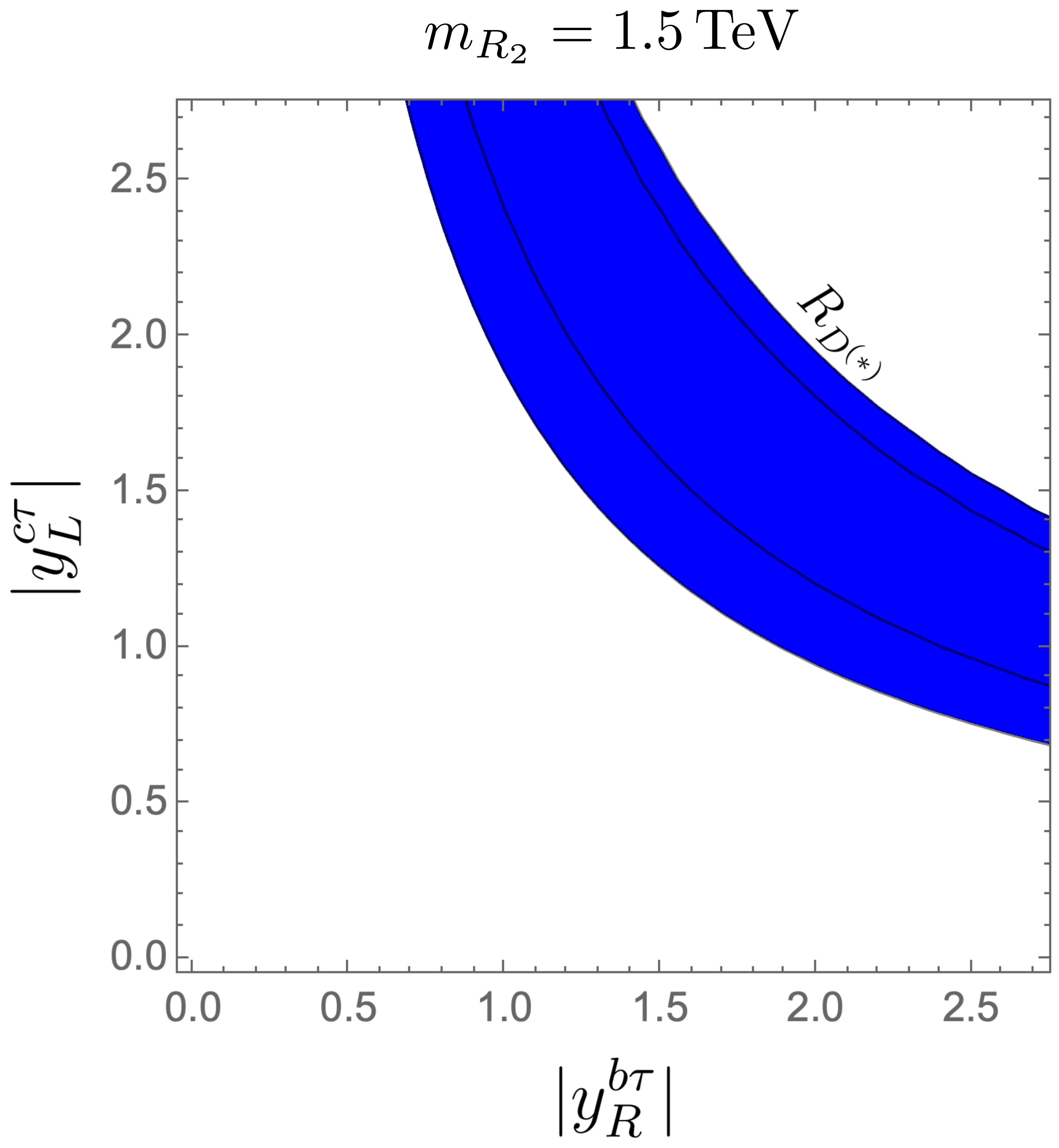
$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$

- Consider minimal coupling texture

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

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

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



*2σ allowed regions

$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$

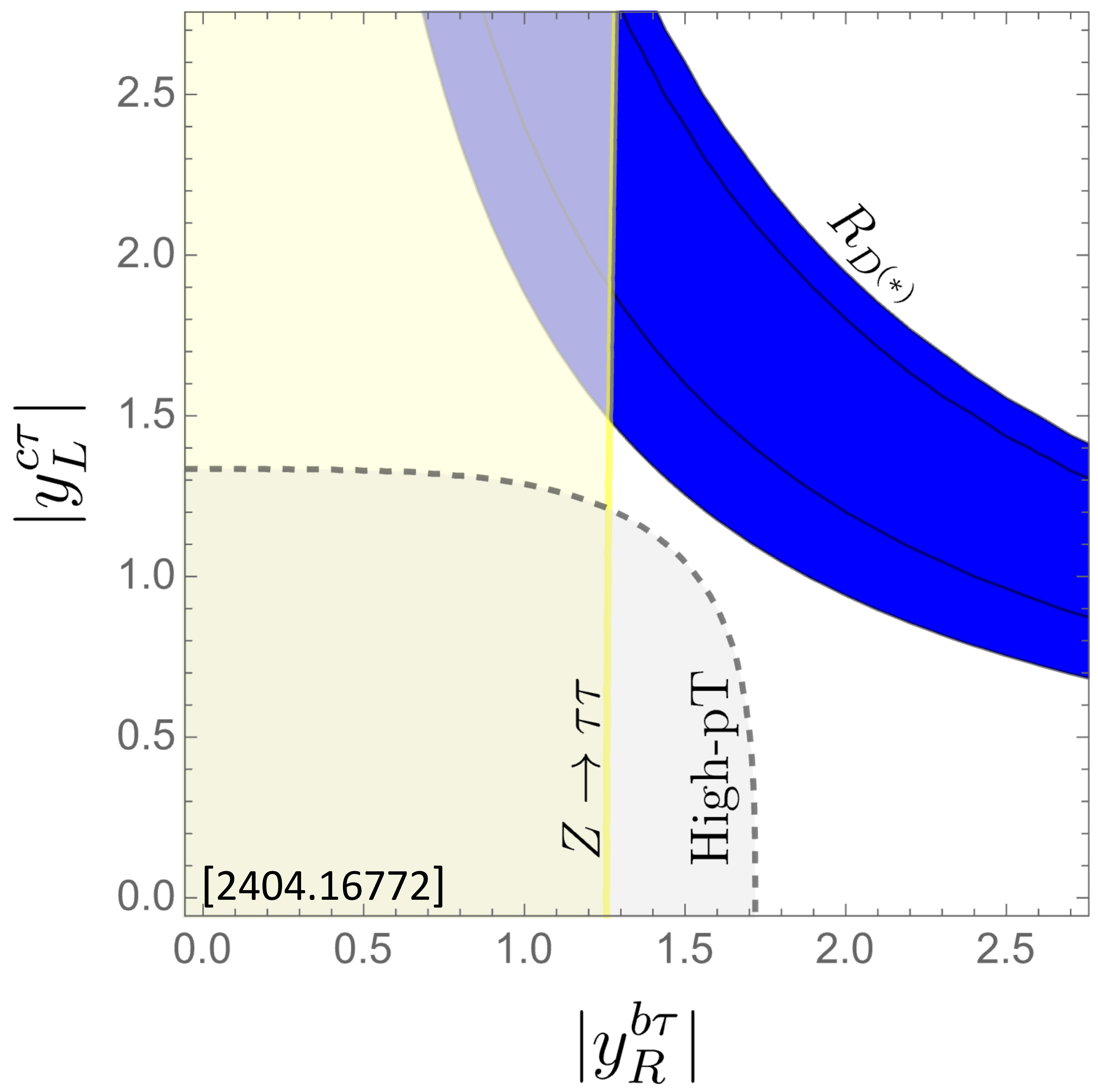
- Consider minimal coupling texture

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

- $R_{D^{(*)}}$ can be accommodated :)
- But: high-p_T - data and constraints from $Z \to \tau\tau$ decay exclude 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

$\tilde{R}_2 = (\mathbf{3}, \mathbf{2}, 1/6)$

- The "opposite" of R_2
  *wrt. to quantum numbers

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

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

$\tilde{R}_2 = (\mathbf{3}, \mathbf{2}, 1/6)$

- The "opposite" of R_2
  *wrt. to quantum numbers

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

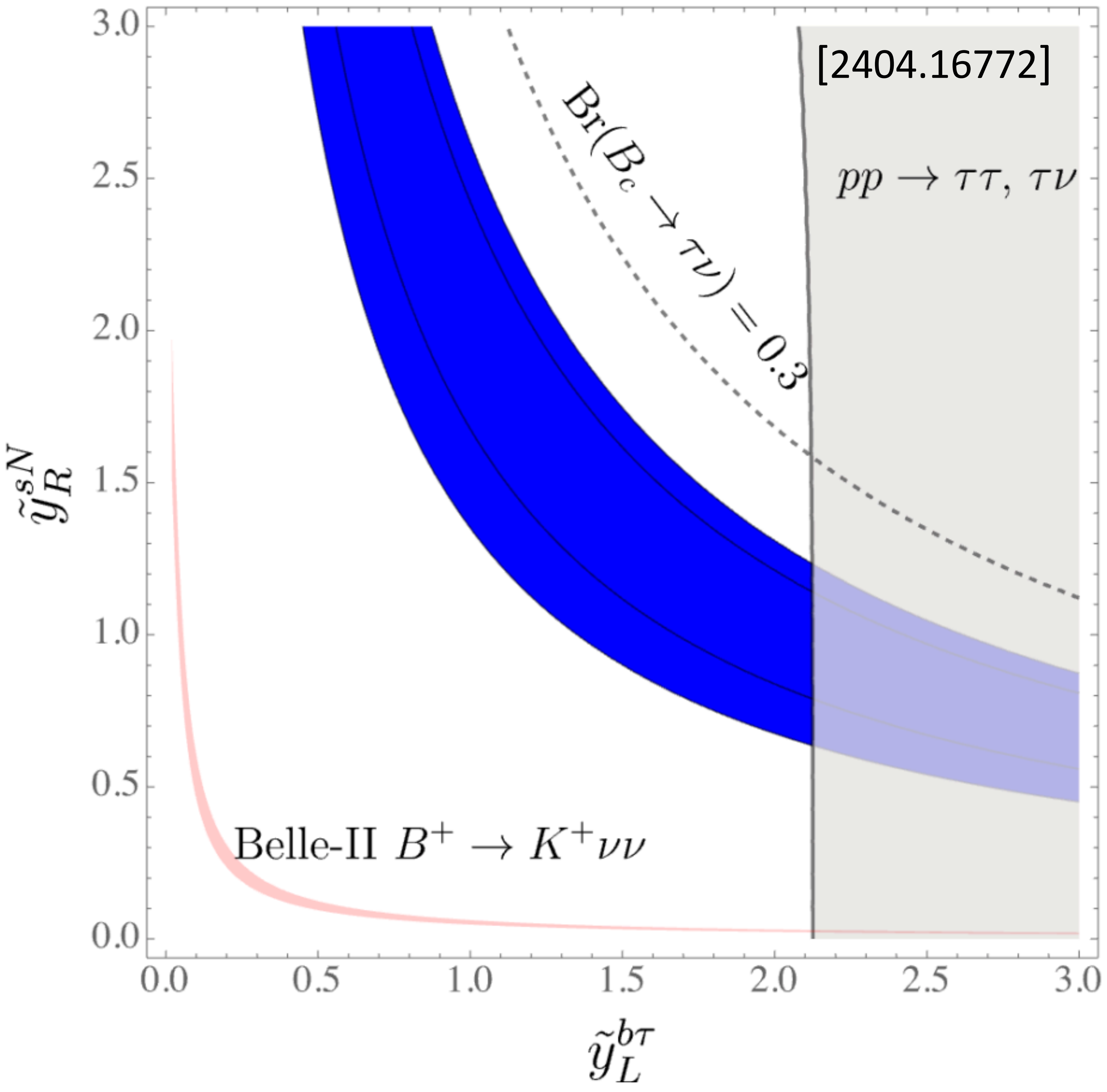
- Again, $R_{D^{(*)}}$ can be accommodated :)
  * if a **right-handed neutrino** is added!

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

- **Modified** High-p_T with right-handed neutrinos

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

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



*2σ allowed regions

$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$

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

- We will focus on three cases:

$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$

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

- We will focus on three cases:

  1. Only left-handed interactions

$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$

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

- We will focus on three cases:

    1. Only left-handed interactions

    2. Left- and right-handed interactions

$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$

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

- We will focus on three cases:

   1. Only left-handed interactions

   2. Left- and right-handed interactions

   3. Only right-handed interactions

$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$

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

- We will focus on three cases:

  1. Only left-handed interactions

  2. Left- and right-handed interactions

  3. Only right-handed interactions

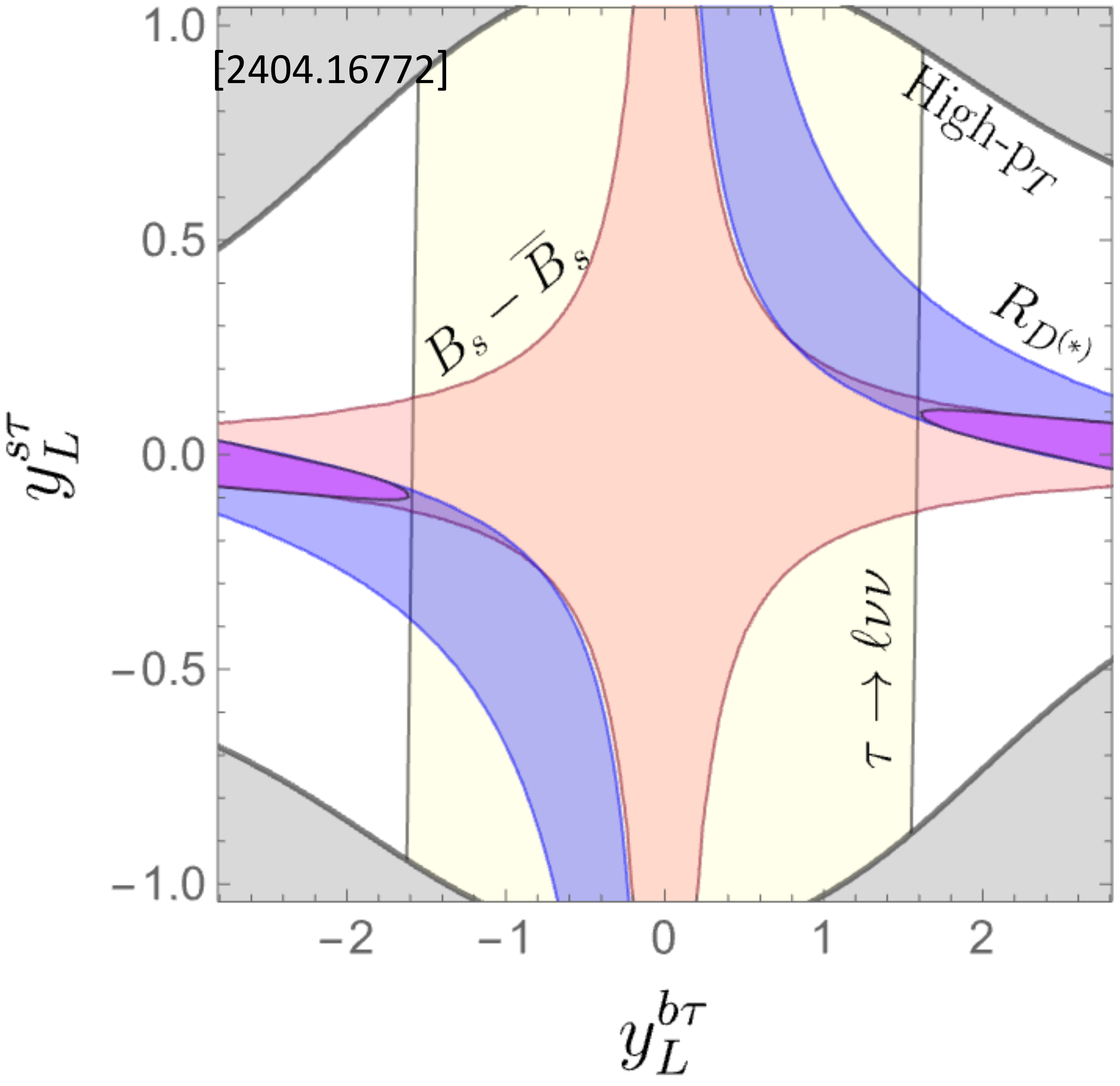
  ⇒ each of them will have specific correlations between flavour observables

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

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

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

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



*2σ allowed regions

- Once again, $R_{D^{(*)}}$ can be accommodated

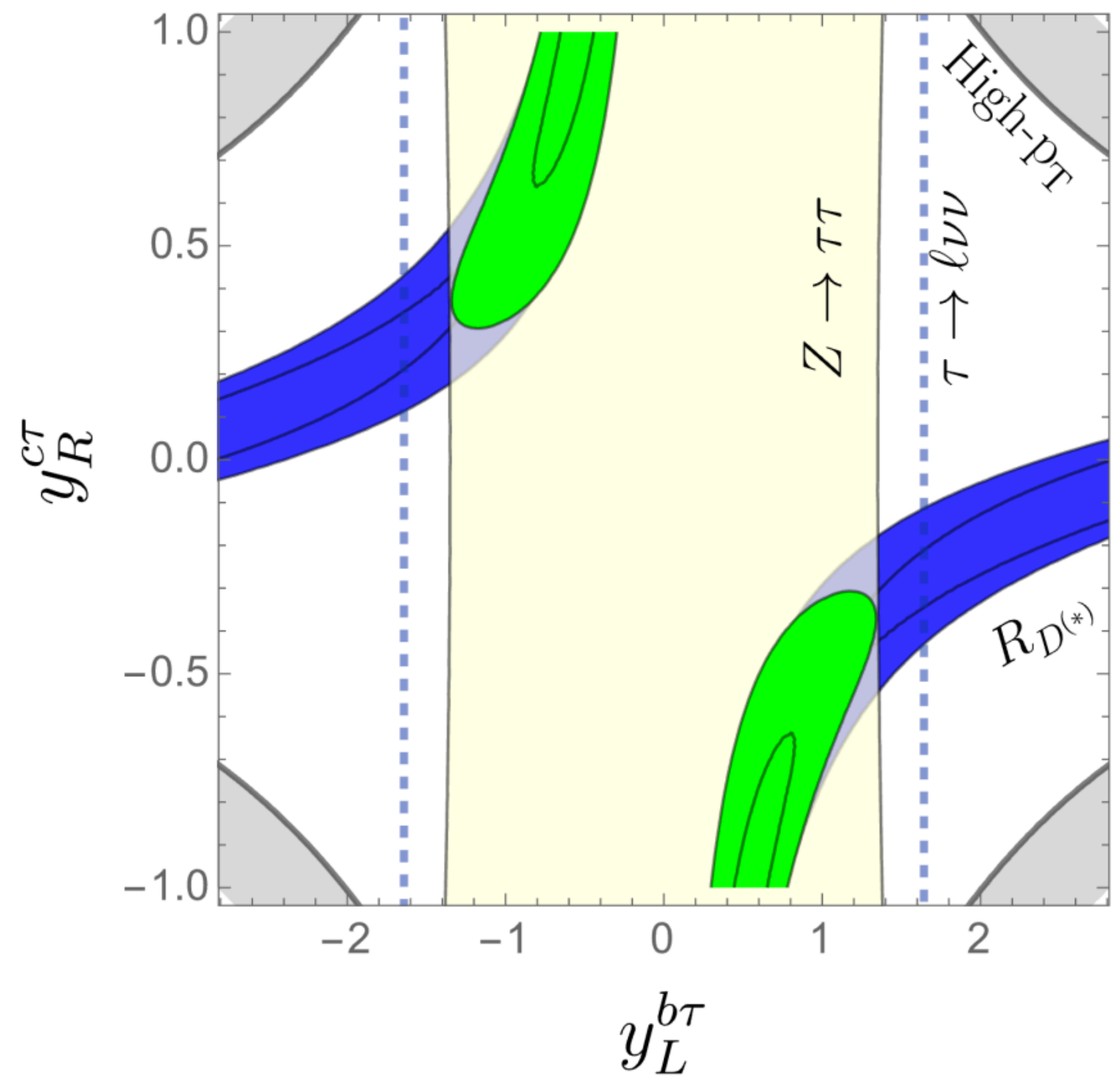
- But this time the effect in $B_s - \overline{B}_s$ and $\tau \to \ell\nu\nu$ is slightly too large

"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

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

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

2008.09548

Predictions with "left- and right-handed" S_1

- Explored 3 different minimal TeV-scale LQ models
  - ⇒Only S_1 with left and right-handed interactions **phenomenologically viable**
- **Can be tested** in $B \to D^{(*)}\tau\nu$ angular observables

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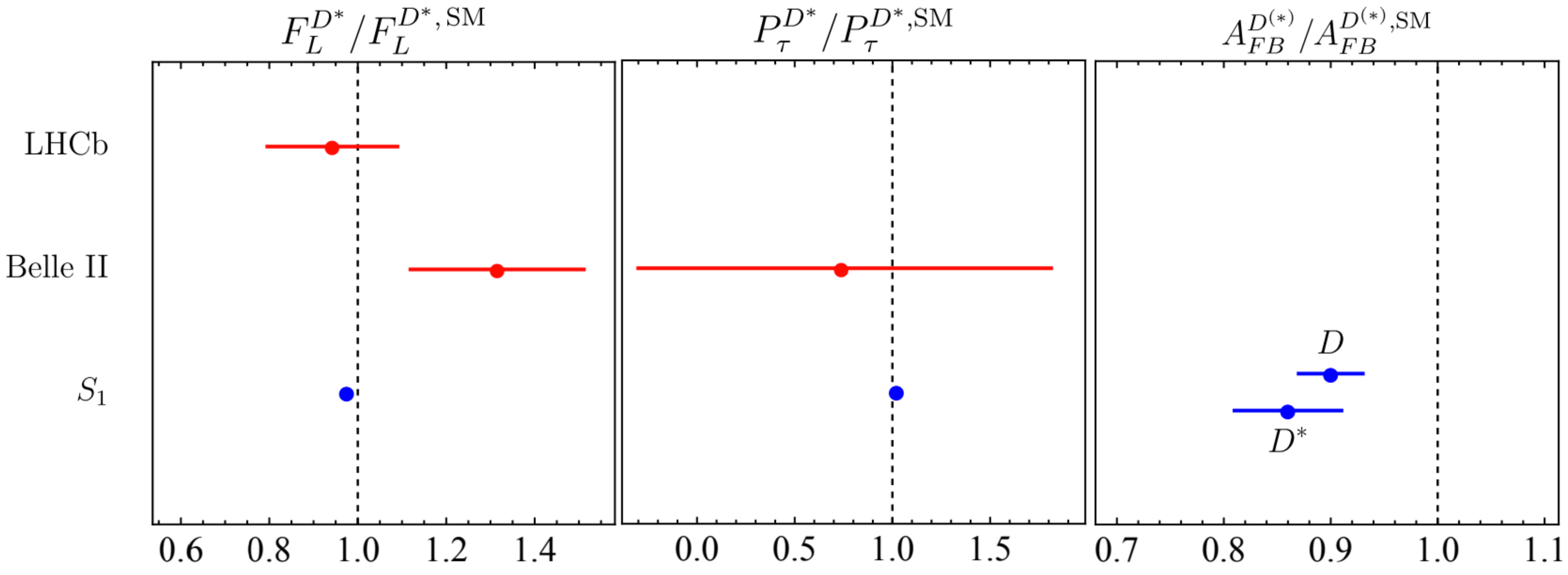
2004.06726
1309.0301
1602.03030
...



$$\frac{d^2\Gamma(D^*)}{dq^2 d\cos\theta_D} = a_{\theta_D}\cos^2\theta_D + b_{\theta_D}\sin^2\theta_D$$

$$a_{\theta_D} \equiv \frac{3}{2}F_L^{D^*} \times \Gamma$$

$$P_\tau^{D^{(*)}} = \frac{\Gamma^+(D^{(*)}) - \Gamma^-(D^{(*)})}{\Gamma^+(D^{(*)}) + \Gamma^-(D^{(*)})}$$

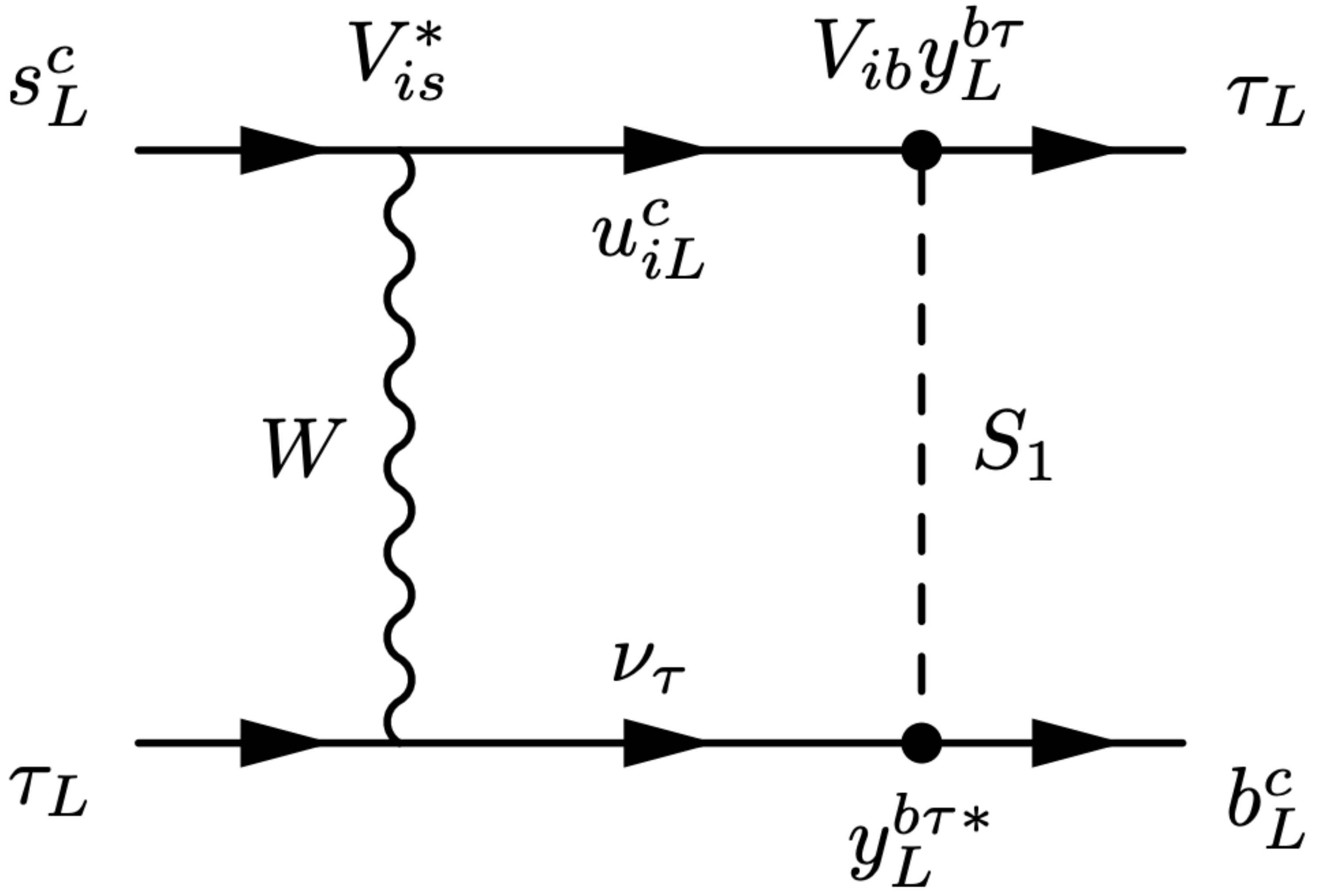
τ helicity

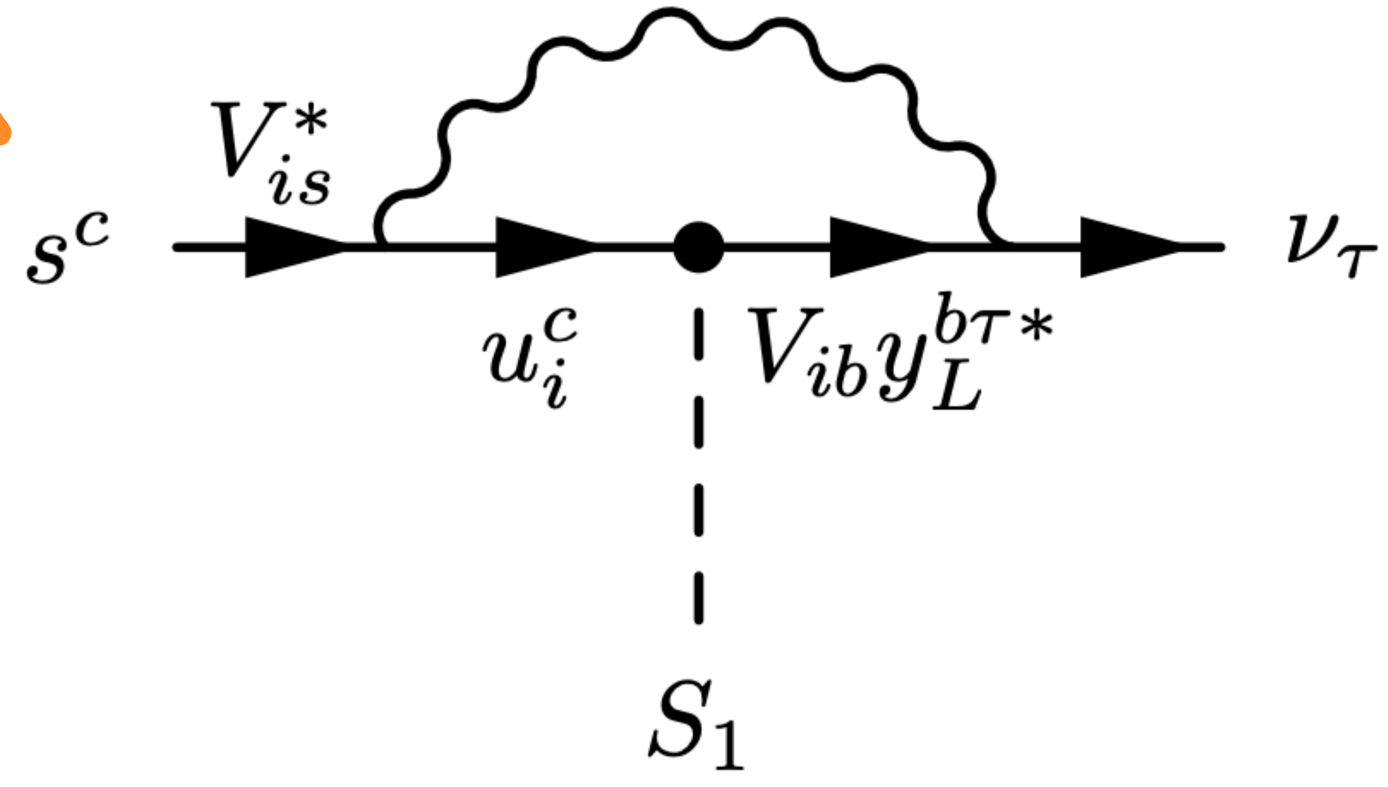
$$A_{FB}^{D^{(*)}} = \frac{1}{\Gamma}\int dq^2 \left(\int_0^1 - \int_{-1}^0\right)\cos\theta_\tau d\Gamma(D^{(*)})$$

Predictions with "left- and right-handed" S_1

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

▷Loop effects in $b \to s\ell\ell$





$$\frac{\mathcal{B}(B_s \to \tau\tau)^{S_1}}{\mathcal{B}(B_s \to \tau\tau)^{\text{SM}}} \in [0.73, 0.98]\,, \quad \frac{\mathcal{B}(B \to K\tau\tau)^{S_1}}{\mathcal{B}(B \to K\tau\tau)^{\text{SM}}} \in [0.73, 0.98]$$

$$\frac{\mathcal{B}(B \to K^{(*)}\nu\nu)^{S_1}}{\mathcal{B}(B \to K^{(*)}\nu\nu)^{\text{SM}}} \in [1.001, 1.02]$$

$B^+ \to K^+ \nu\nu$ decay

- Relatively clean theoretical prediction 1409.4557, 2301.06990

  $\Rightarrow$ No large uncertainties beyond the form factors

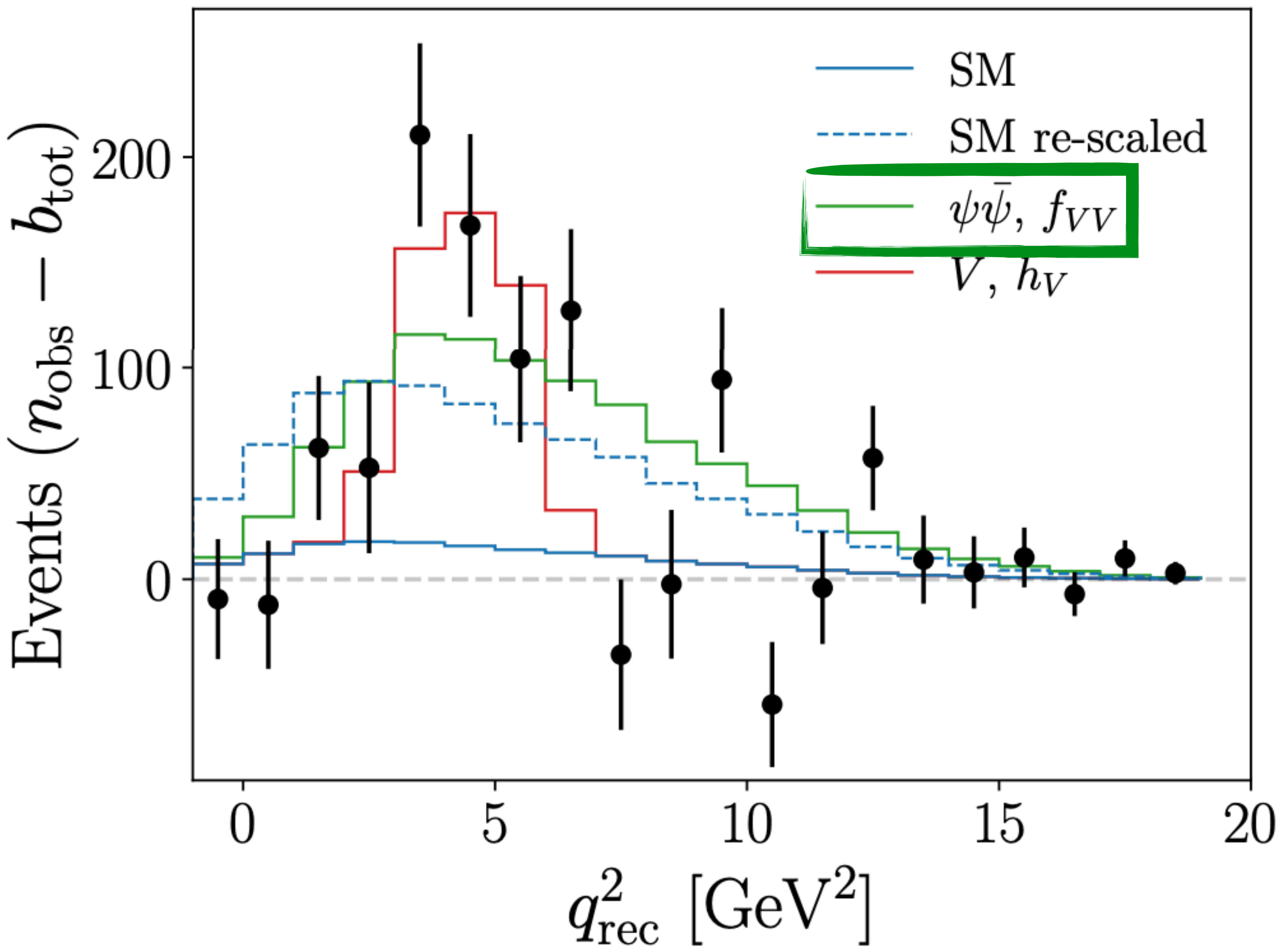
- New Belle II measurement shows $\sim 2.7\sigma$ **deviation from the SM prediction**

$$\Rightarrow \begin{cases} \mathcal{B}(B^+ \to K^+\nu\nu)^{\rm SM} = 4.4(3) \times 10^{-6} \\ \mathcal{B}(B^+ \to K^+\nu\nu)^{\rm exp.} = 2.35(67) \times 10^{-5} \end{cases}$$

- The new neutral lepton of mass ~ 0.6 GeV fits the binned data best

  2403.13887
  2312.12507

2403.13887



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?**

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

Inert S_1 (“right-handed”)

- Right-handed couplings

  $\Rightarrow$no **CKM mixing**

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

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

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

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

Also allows an enhancing effect in $B \to K^{(*)}$ 'inv'

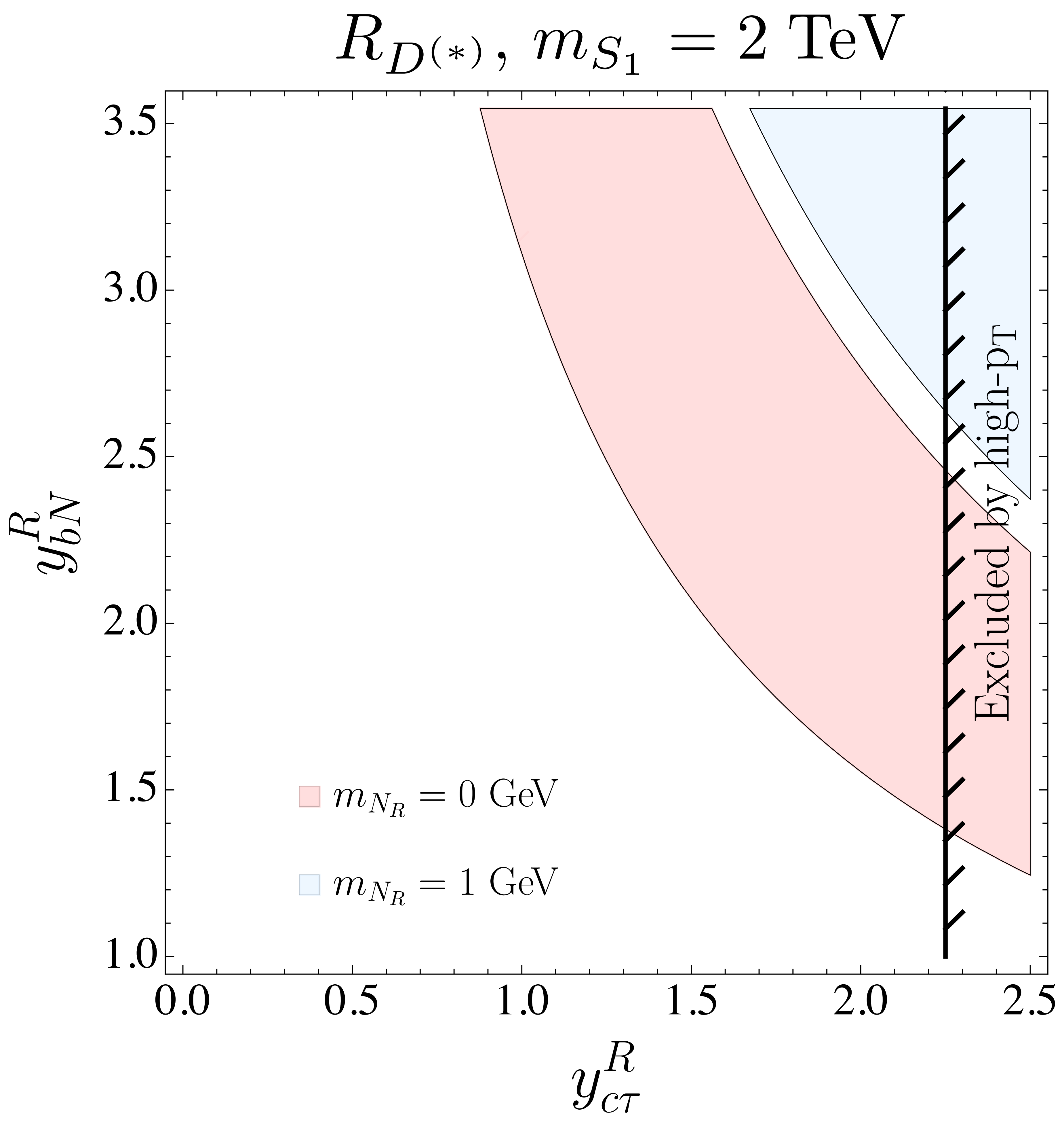
Inert S_1 ("right-handed")

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

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

- Only RH interactions

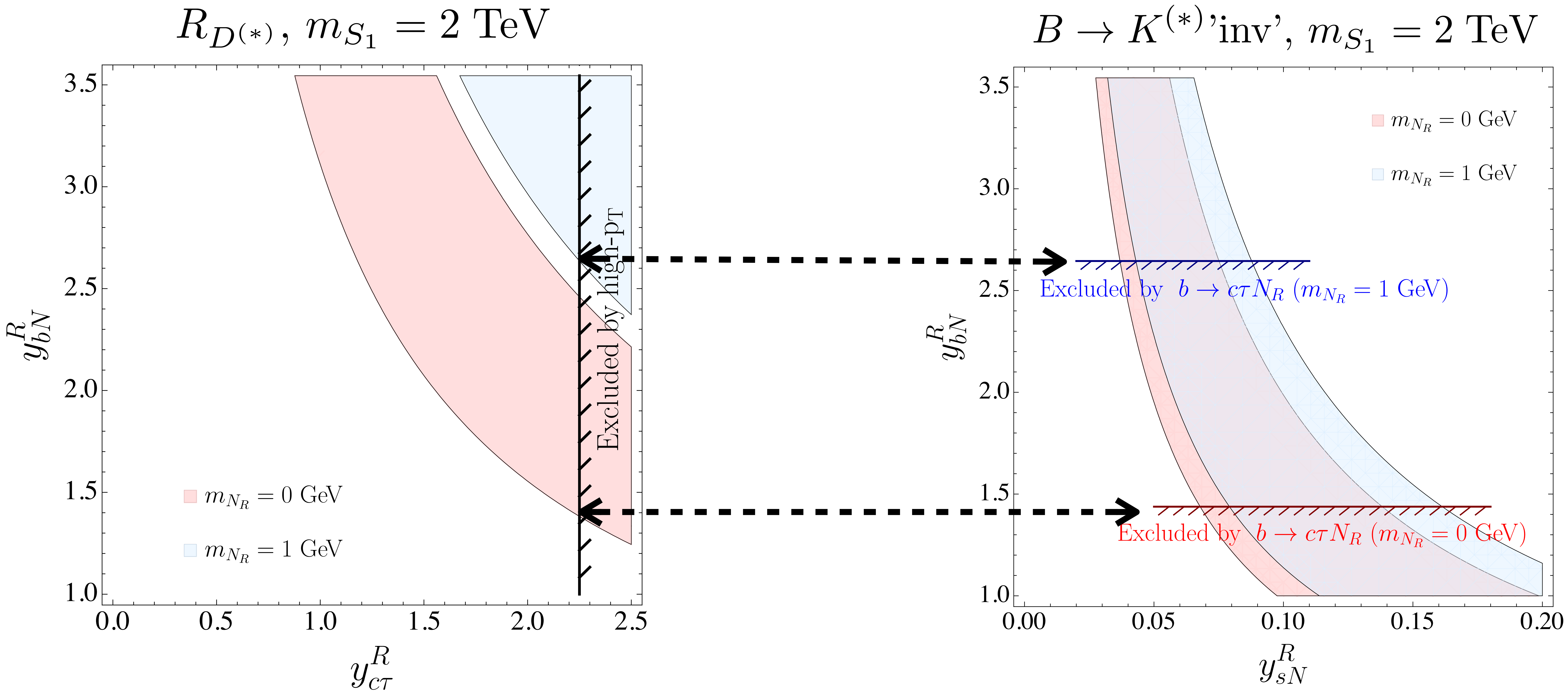
  $\Rightarrow$ Evaded $B_s - \overline{B}_s$ mixing, also $Z \to \tau\tau$ and $\tau \to \ell\nu\nu$



*2σ allowed regions

Inert S_1 (“right-handed”)

- Excess in $\mathscr{B}(B^+ \to K^+$ 'inv') can also be accommodated :)
- Besides $R_{D^{(*)}}$ and $B \to K^{(*)}$'inv', practically no other constraining observable



*2σ allowed regions

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' $(R_{J/\psi})$

- Particularly interesting:

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

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

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

Deviate from SM in the presence of RHN

Left almost unchanged

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' ($R_{J/\psi}$)

- Particularly interesting:

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

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$F_L^{D^*}$	$0.46(1)$	$0.46(1)$	$0.46(1)$	$0.45(1)$

$\Rightarrow$ Only some observables experimentally measured, poor accuracy

$\Rightarrow$ Improvements in Belle II?

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 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)**, enhances also $B \to K^{(*)}\nu\nu$

    ⇒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!