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New Physics implications of the B-physics anomalies

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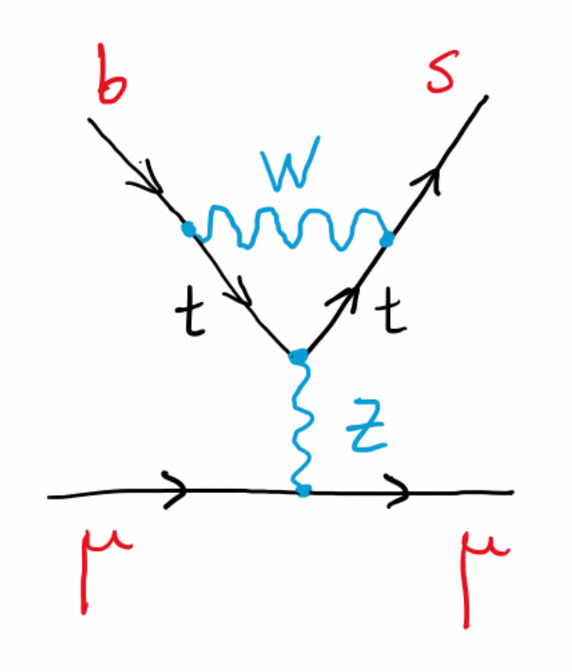
The B-physics anomalies

Hints of Lepton Flavour Universality Violation in semileptonic B decays

$\boldsymbol{b \to s\ell^+\ell^-}$

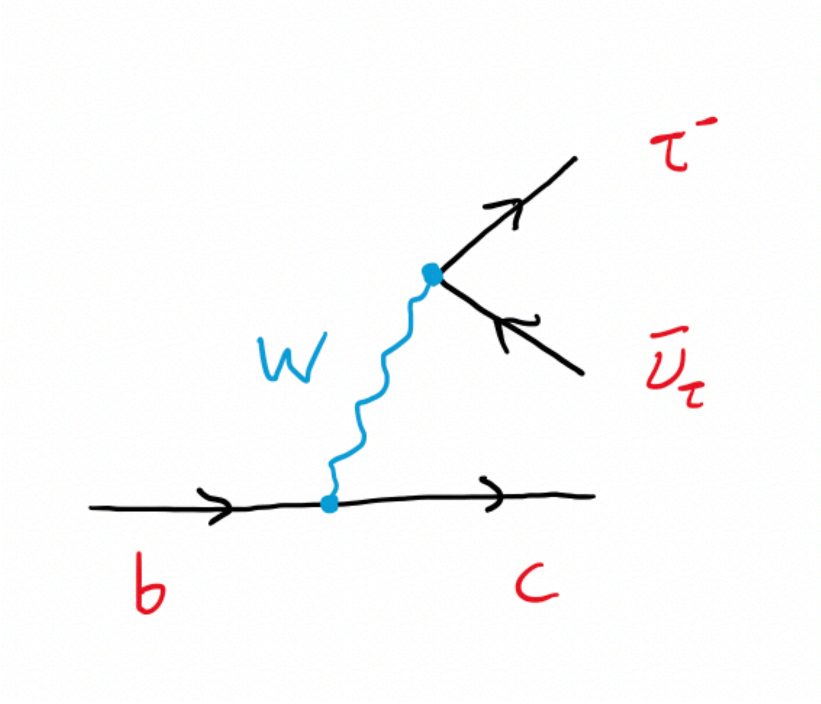
μ/e ~~universality~~



$> 4\,\sigma$

$\boldsymbol{b \to c\tau\nu}$

$\tau/\mu\,,e$ ~~universality~~

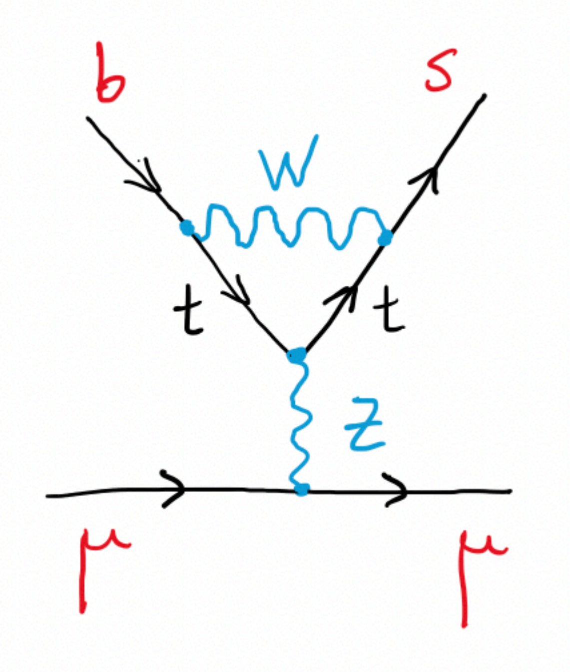


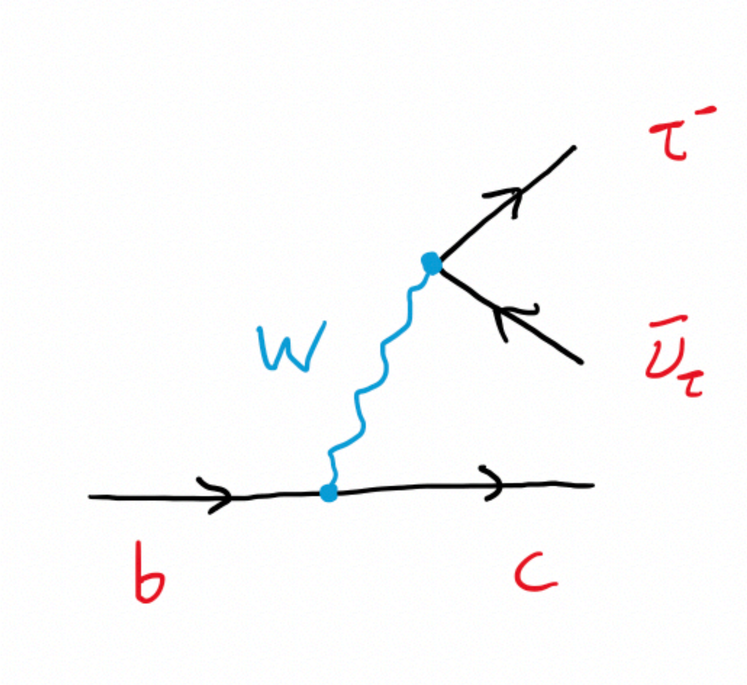
$\sim 3\,\sigma$

Towards a combined explanation of the anomalies

Taken together, these are a very significant set of deviations from the SM

→ It is worth looking for a **combined explanation** in terms of New Physics!





$3_Q \to 2_Q 2_L 2_L \ll 3_Q \to 2_Q 3_L 3_L$

~20% of a SM **loop** effect

~15% of a SM **tree-level** effect

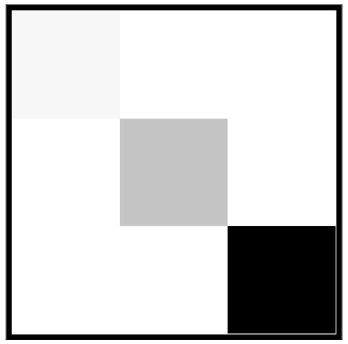
The only source of **lepton flavor universality violation** in the SM (Yukawas) follows a similar trend: $y_e \ll y_\mu \ll y_\tau$…. Are these anomalies connected to them?

A NP hint to the SM flavor puzzle?

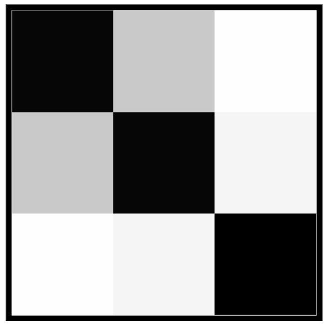
The SM Yukawa sector is characterized by 13 parameters
[3 lepton masses + 6 quark masses + 3+1 CKM parameters]

… whose values do not look at all accidental

$M_{u,d,e} \sim$



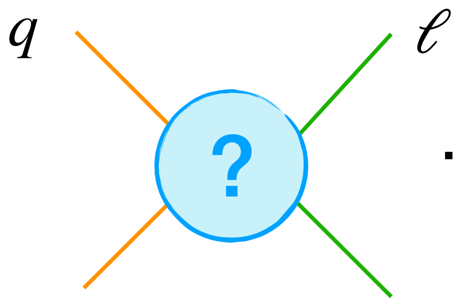
$V_{\rm CKM} \sim$



✓ The flavor anomalies seem to suggest a similar trend: large NP effects in 3rd generation, gradually smaller effects in the light generations

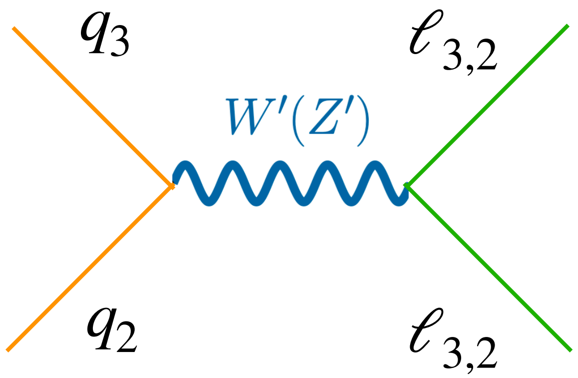
✓ Recent theoretical progress connecting the anomalies to the SM flavor hierarchies

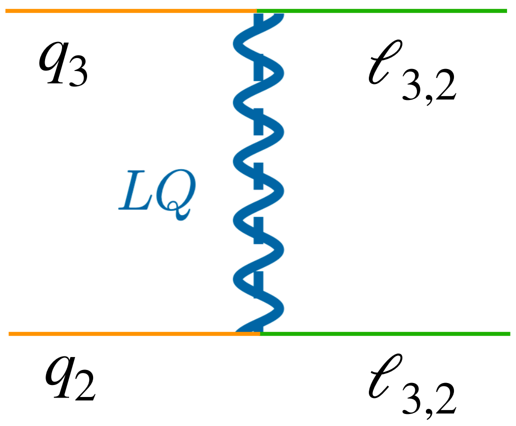
[Bordone, Cornella, JFM, Isidori 1712.01368; Greljo, Stefanek 1802.04274; Allanach, Davighi 1809.01158,…]



…..Which mediator?

Which mediator?





Only few possibilities are available

- ★ **Minimal W'/Z' models** in tension with high-p_T data ($pp \to \tau\tau$ tails)

  [Faroughy et al. 1609.07138]

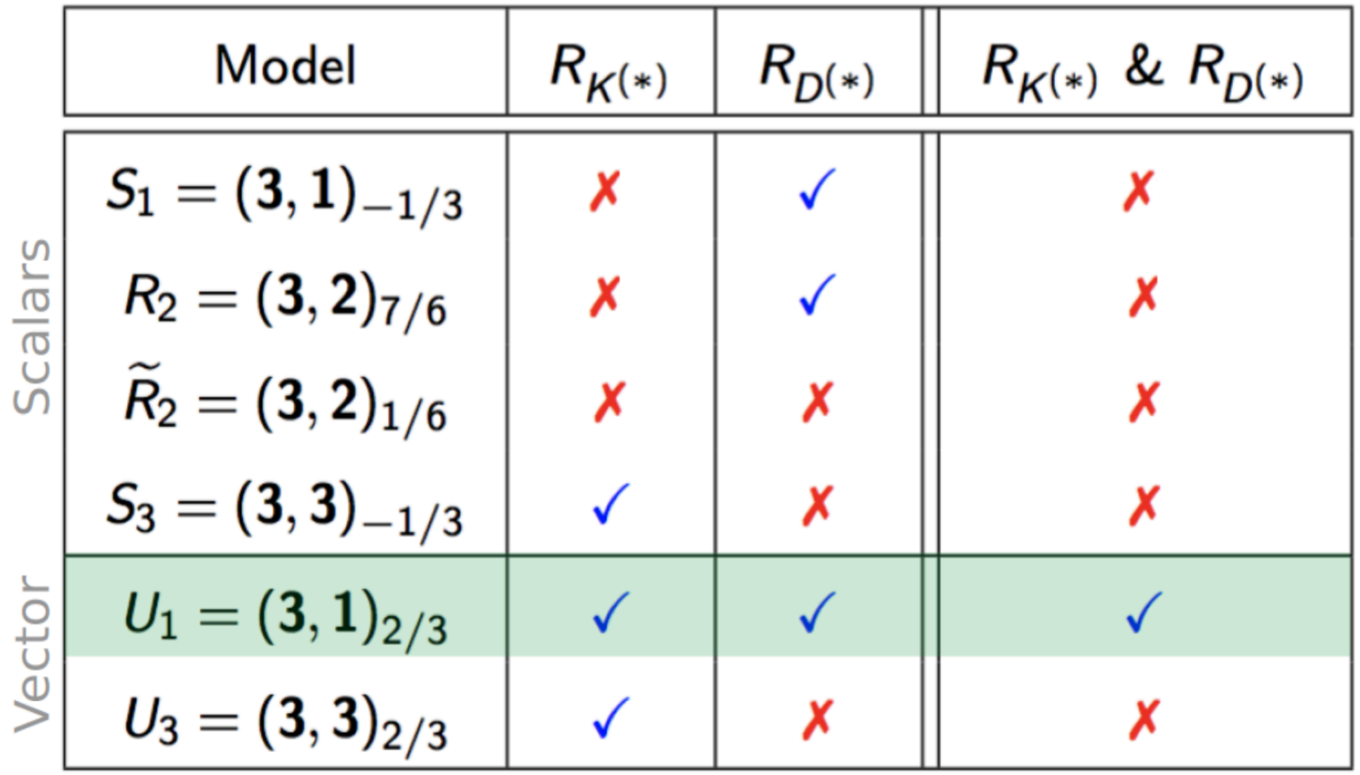
  W' + light ν_R in better shape but still in tension with $pp \to \tau\nu$ tails

  [Greljo et al. 1811.07920]

- ★ **Leptoquarks** (scalars or vectors) are the best candidates so far

  ✓ no 4-lepton (LFV, LFUV) or 4-quark processes ($\Delta F = 2$) at tree level

The main suspects



	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
Scalars	$S_1 = (\mathbf{3},\mathbf{1})_{-1/3}$	✗	✓	✗
	$R_2 = (\mathbf{3},\mathbf{2})_{7/6}$	✗	✓	✗
	$\widetilde{R}_2 = (\mathbf{3},\mathbf{2})_{1/6}$	✗	✗	✗
	$S_3 = (\mathbf{3},\mathbf{3})_{-1/3}$	✓	✗	✗
Vector	$U_1 = (\mathbf{3},\mathbf{1})_{2/3}$	✓	✓	✓
	$U_3 = (\mathbf{3},\mathbf{3})_{2/3}$	✓	✗	✗

[Angelescu, Bečirević, Faroughy, Sumensary, 1808.08179]

Three viable options in the market:

★ U_1 + UV completion

[di Luzio, Greljo, Nardecchia 1708.08450;
Calibbi, Crivellin, Li 1709.00692;
Bordone, Cornella, JF, Isidori 1712.01368;
Barbieri, Tesi, 1712.06844…]

★ $S_1 + S_3$

[Crivellin, Muller, Ota 1703.09226;
Buttazzo et al. 1706.07808;
Marzocca 1803.10972]

★ $S_3 + R_2$ [See talk by Ilja Doršner]

[Bečirević et al., 1806.05689]

The vector leptoquark (U_1) brings some interesting theoretical features into the game

- ✓ Low-scale bottom-tau unification. Possible link to Pati-Salam unification
- ✓ Connections to the SM flavor puzzle

The U_1 leptoquark solution

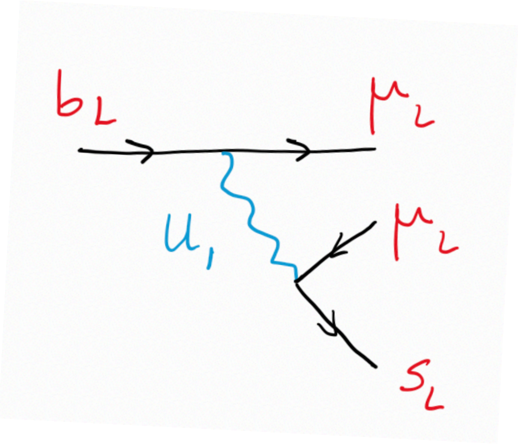
$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta^L_{i\alpha}(\bar{q}^i_L \gamma_\mu \ell^\alpha_L) - \beta^R_{i\alpha}(\bar{d}^i_R \gamma_\mu e^\alpha_R)\right] + \mathrm{h.c.} \qquad [M_U \sim 2 - 7\ \mathrm{TeV}]$$

Flavor structure$^{(*)}$

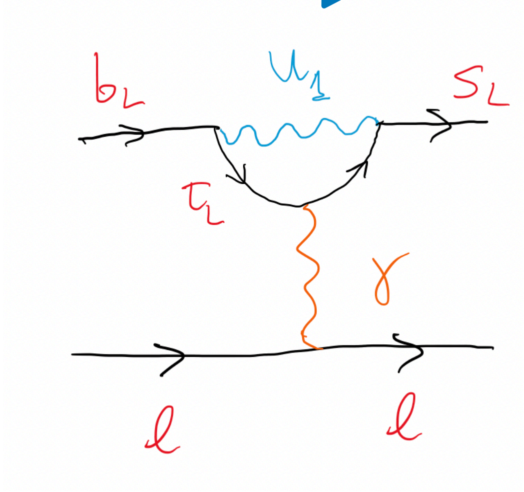
$$\beta^L \sim \begin{array}{cc} \begin{array}{ccc} \ell_1 & \ell_2 & \ell_3 \end{array} & \\ \begin{pmatrix} 0 & 0 & 10^{-2} \\ 0 & 10^{-2} & 10^{-1} \\ 0 & 10^{-1} & 1 \end{pmatrix} & \begin{array}{c} q_1 \\ q_2 \\ q_3 \end{array} \end{array} \qquad \beta_R \sim \begin{array}{cc} \begin{array}{ccc} e_R & \mu_R & \tau_R \end{array} & \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \mathcal{O}(1) \end{pmatrix} & \begin{array}{c} d_R \\ s_R \\ b_R \end{array} \end{array}$$

C_{V_L}

C_{S_R}



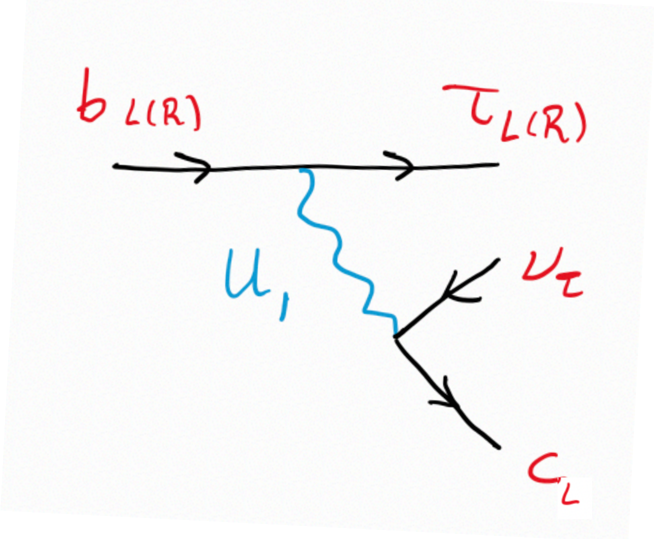
$$\Delta C_9^\mu = -\Delta C_{10}^\mu$$



$$\Delta C_9^{e,\mu,\tau}$$

[Crivellin et al., 1807.02068]

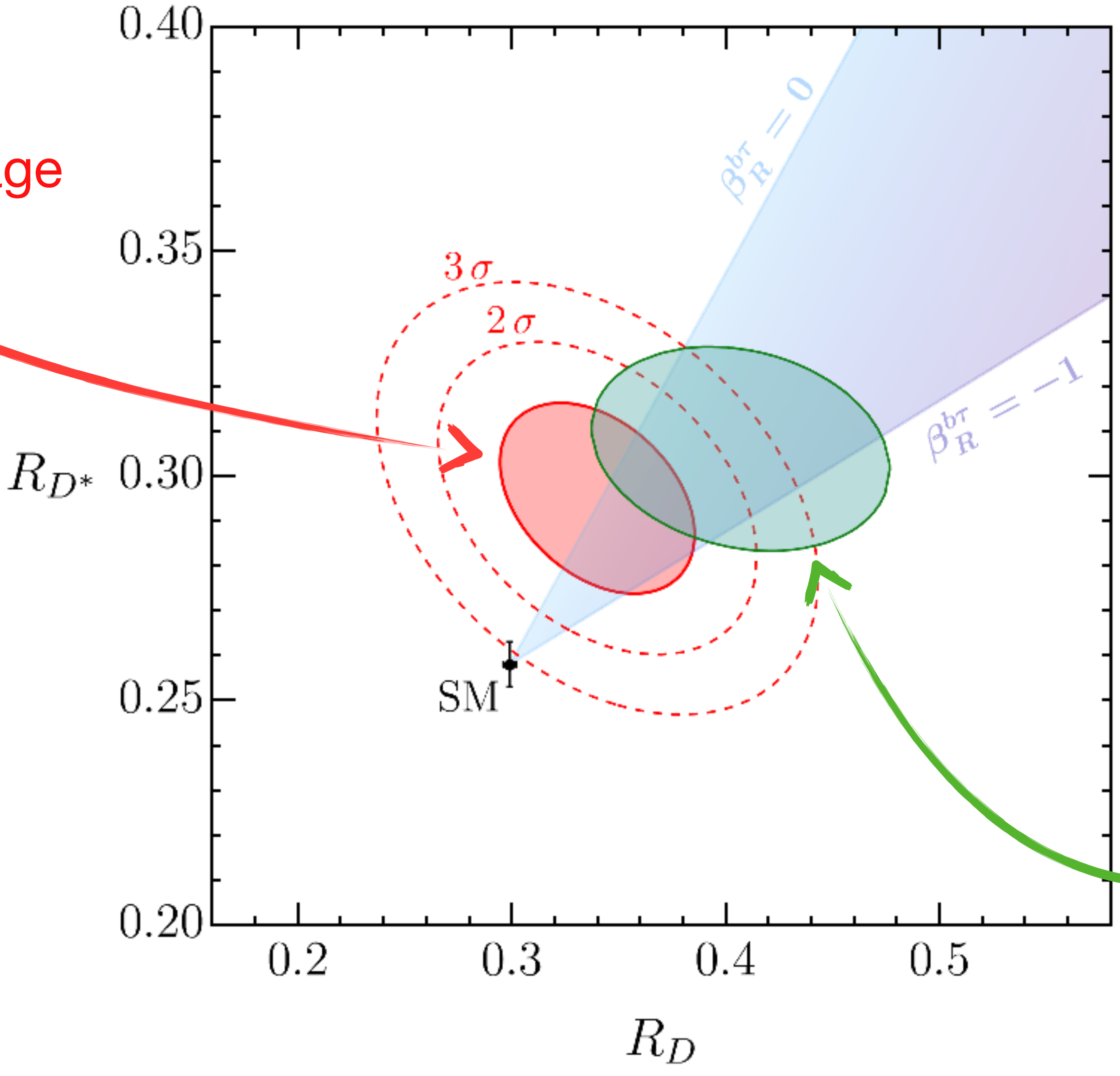
$b \to s\ell\ell \ll R(D^{(*)})$



$(*)$ N.B.: Deviations from this structure highly constrained by low-energy flavor data

Which value of $\beta_{b\tau}^{R}$? $R(D^{(*)})$ projections

New world average



U_1 leptoquark projections

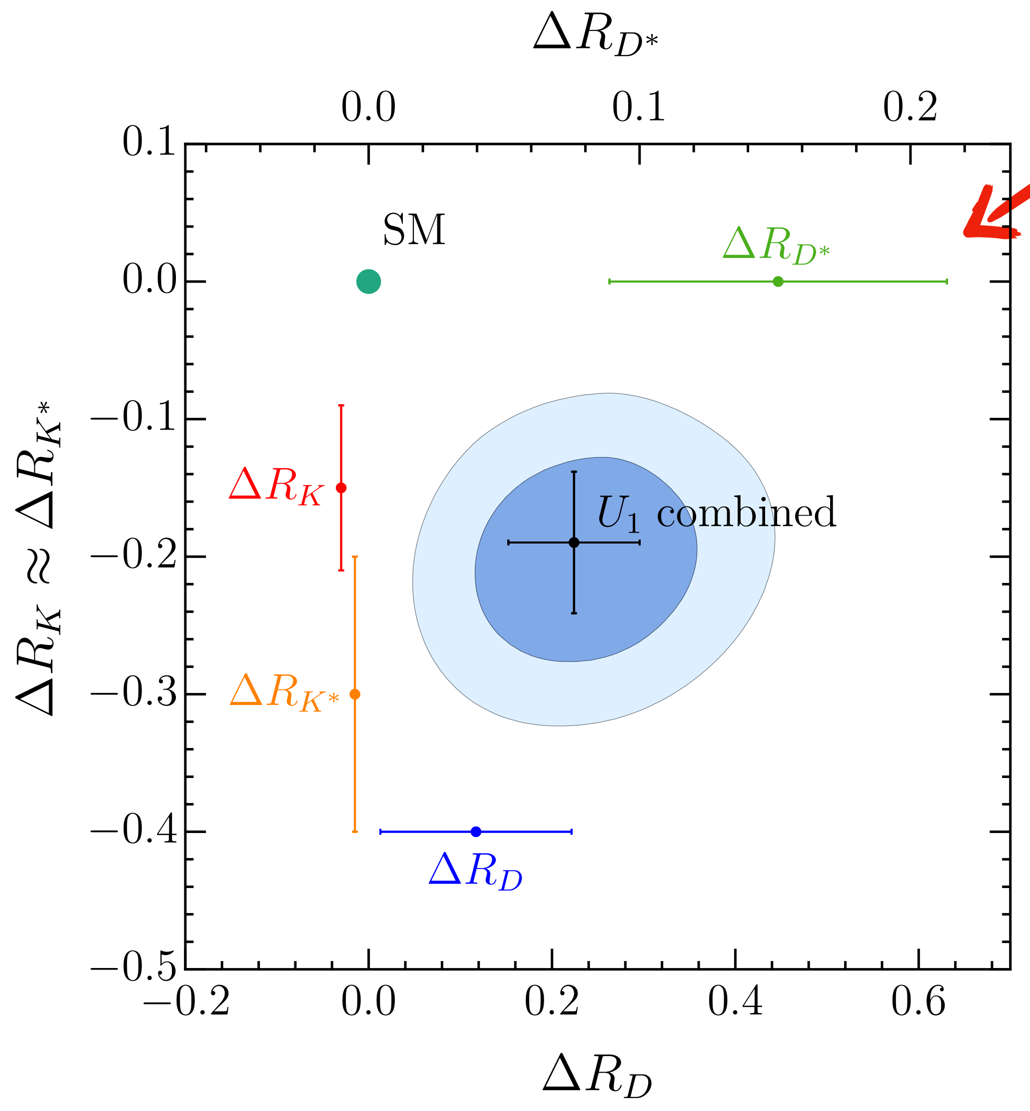
HFLAV world average (pre-Moriond)

Differential distributions, polarizations,… can also be different from the SM

Low-energy fit results

For both extreme cases, the low-energy fit (in particular to the anomalies) is very good!

LH + RH ($\beta^R_{b\tau} = 1$)

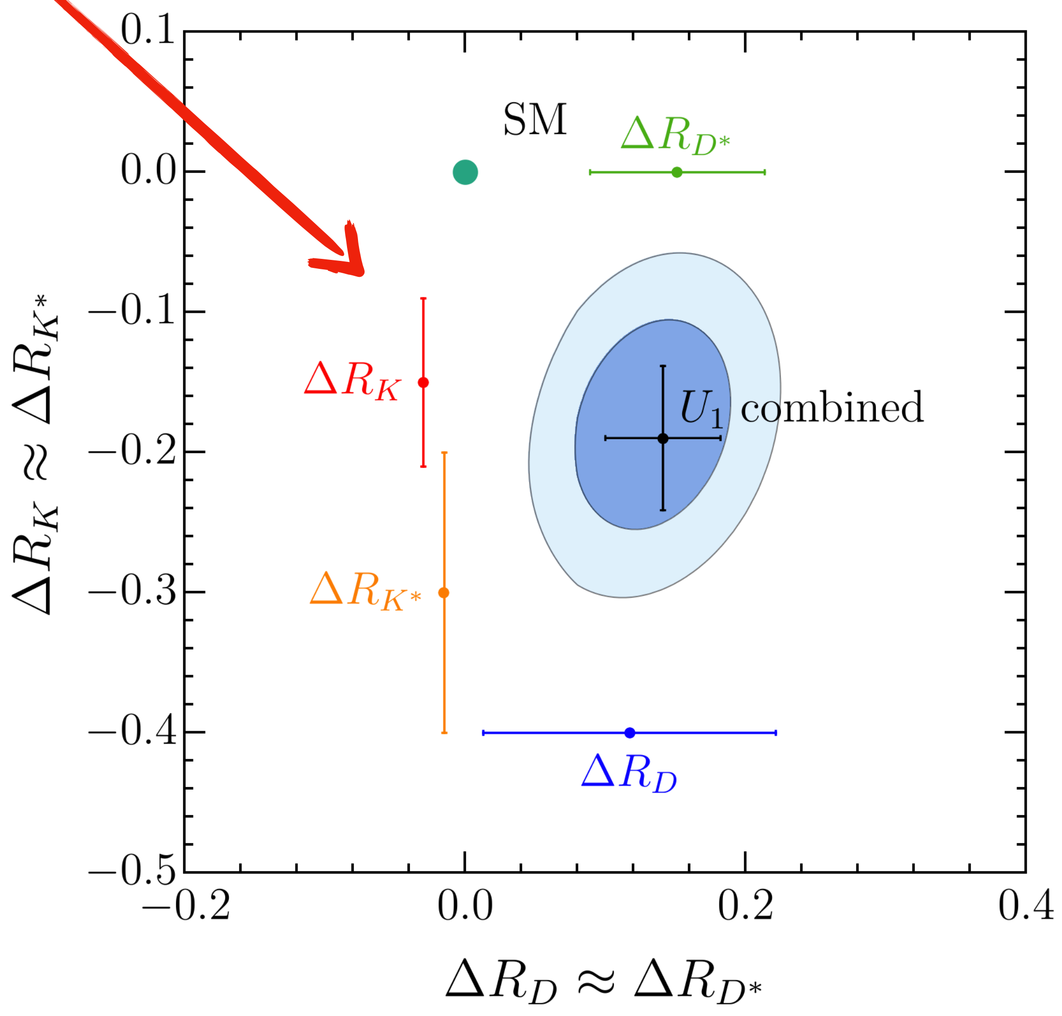


NP scale naturally higher
(thanks to the C_{S_R} contribution)

[Cornella, JFM, Isidori, 1704.06659]

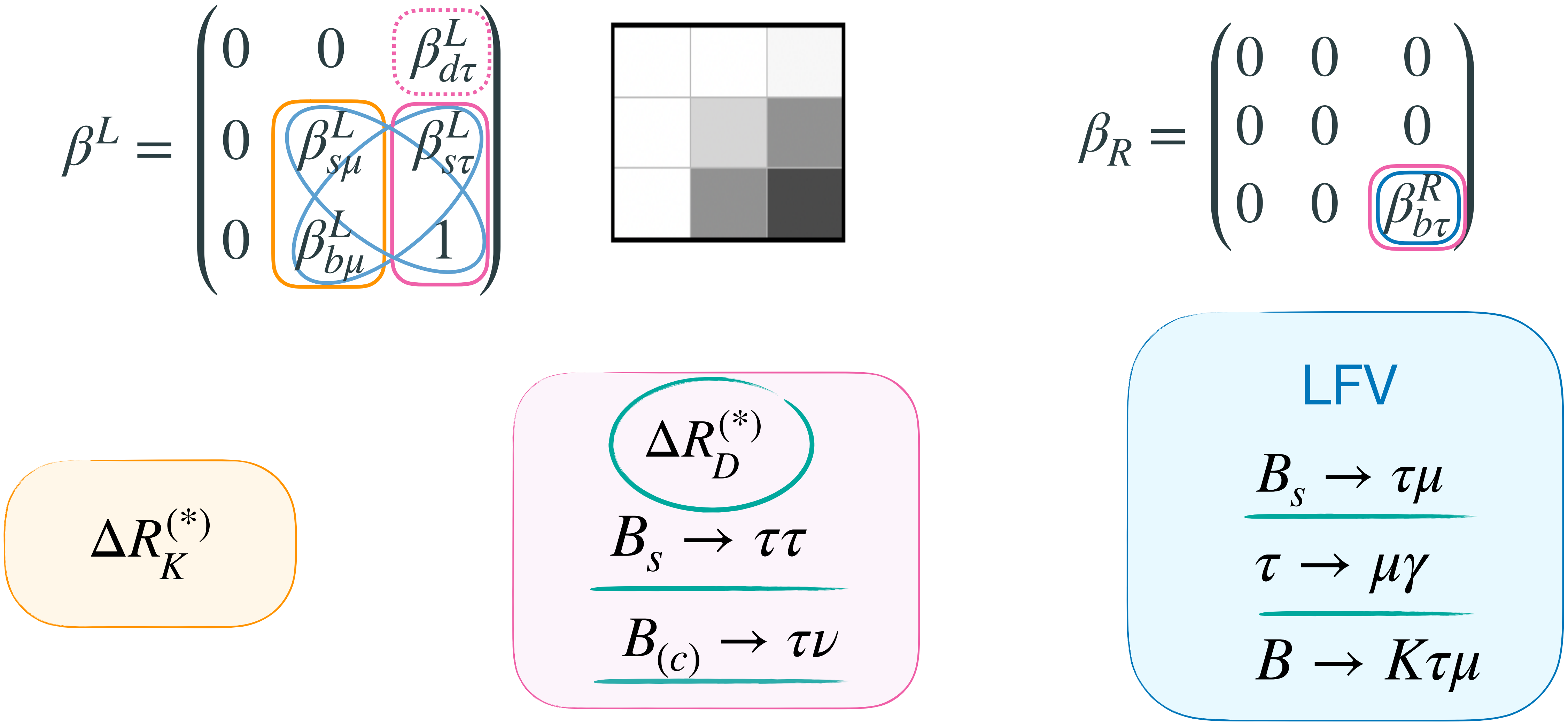
Experiment
@ 1σ

LH only ($\beta^R_{b\tau} = 0$)



Slightly better fit
(due to the new Belle measurement of $R(D^{(*)})$)

Low-energy implications of the U_1 leptoquark



$$\beta^L = \begin{pmatrix} 0 & 0 & \beta^L_{d\tau} \\ 0 & \beta^L_{s\mu} & \beta^L_{s\tau} \\ 0 & \beta^L_{b\mu} & 1 \end{pmatrix}$$

$$\beta_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta^R_{b\tau} \end{pmatrix}$$

$\Delta R_K^{(*)}$

$\Delta R_D^{(*)}$

$B_s \to \tau\tau$

$B_{(c)} \to \tau\nu$

LFV

$B_s \to \tau\mu$

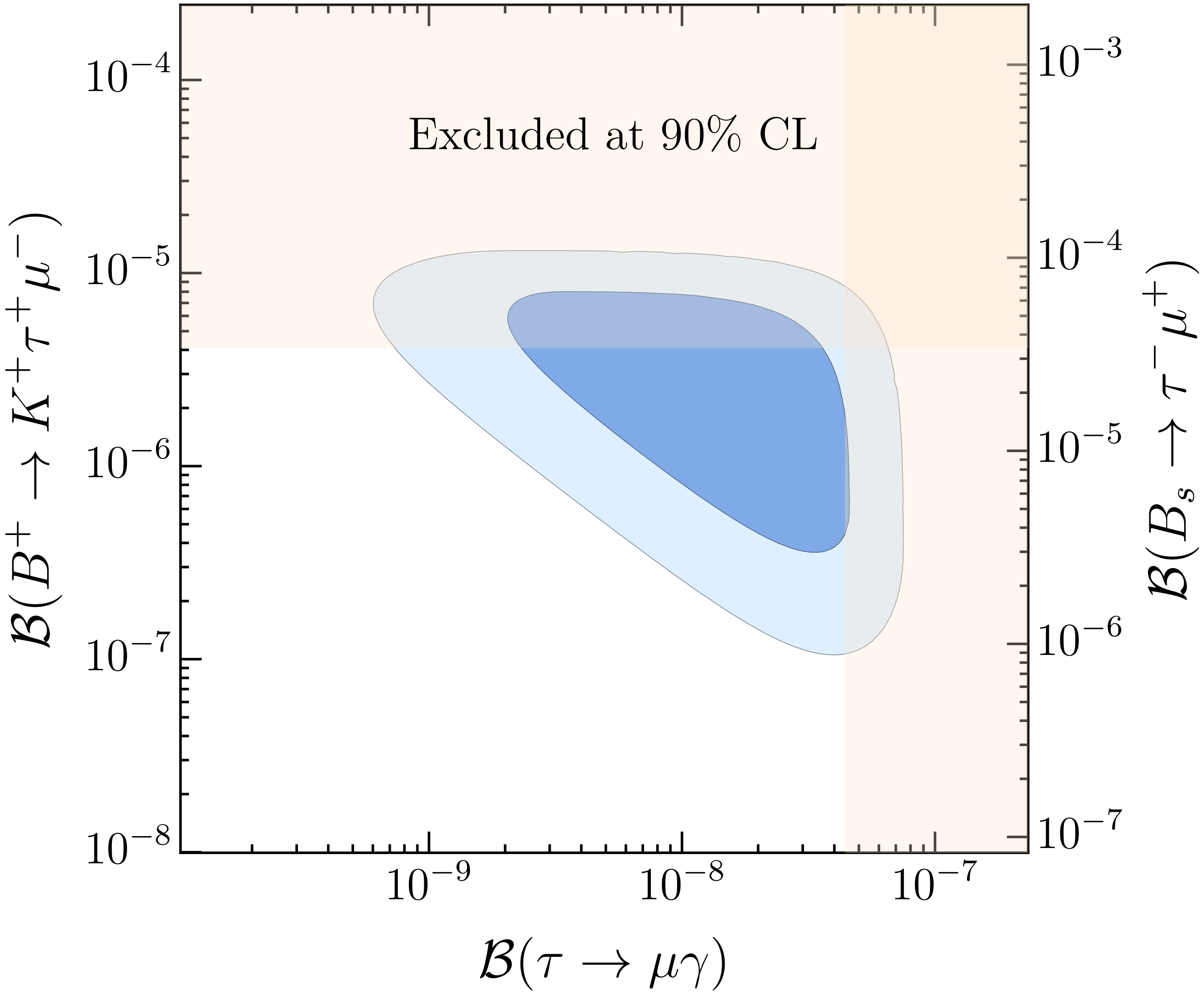
$\tau \to \mu\gamma$

$B \to K\tau\mu$

Non-zero values of $\beta^R_{b\tau}$ have a huge impact on the low energy phenomenology:

- ✓ Different NP contribution for $R(D)$ & $R(D^*)$
- ✓ Chiral-enhanced NP effects (hence very large) in some decays
- ✓ Larger NP scale possible, i.e. larger values for M_U available

LFV in $\tau \to \mu$ transitions $(\beta_{b\tau}^{R} = 1)$



[Cornella, JFM, Isidori, 1903.11517]

Large $\tau\mu$ LFV is expected

→ strong enhancement of $B_s \to \tau\mu\,,\, B \to K\tau\mu\,,\, \tau \to \mu\gamma$ **if $\beta_R^{b\tau} \sim 1$**

$$\mathscr{B}(\tau \to \mu\gamma) \sim 10^{-9}$$

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

$$\mathscr{B}(B_s \to \tau^+\mu^-) \sim 10^{-5}$$

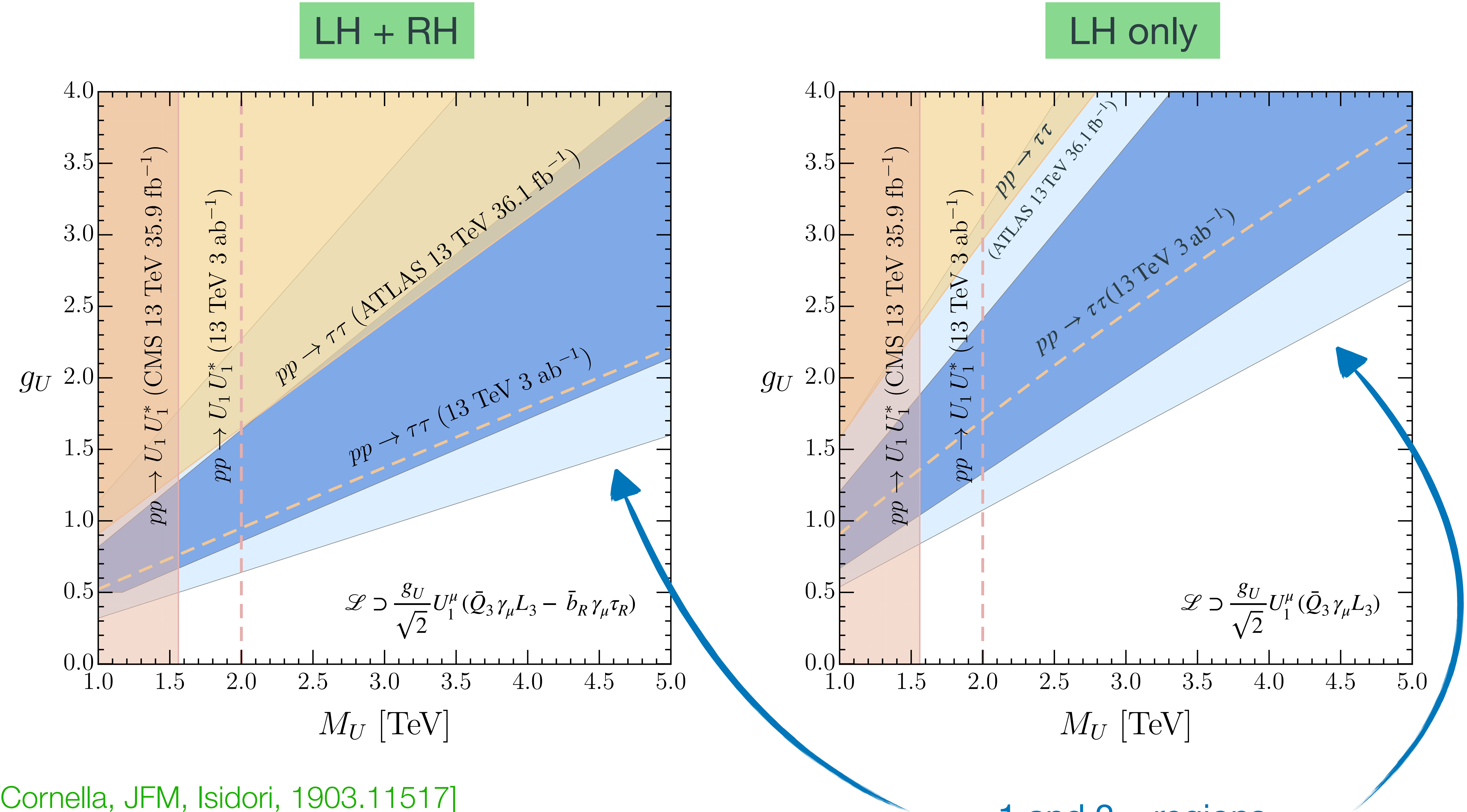
★ Very recent measurement of $\mathscr{B}(B_s \to \tau\mu)$

$$\mathscr{B}(B_s \to \tau\mu) < 3.4 \times 10^{-5}$$

[LHCb, 1905.06614]

High-pT + Low energy

[High-pT bounds from Baker, JFM, Isidori, König, 1901.10480]



1 and 2 σ regions
preferred by the low-energy fit

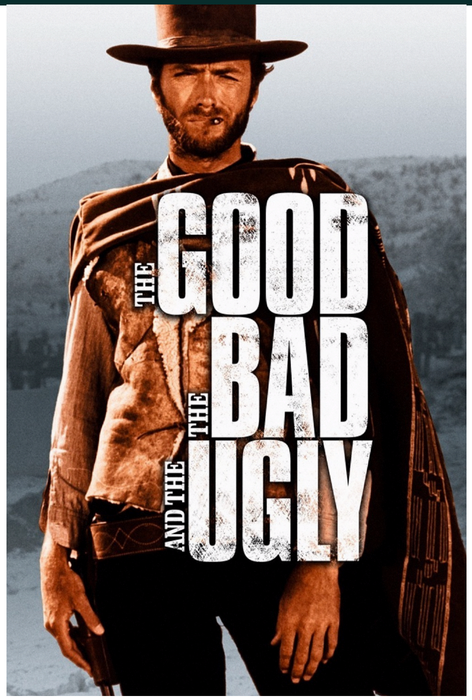
[Cornella, JFM, Isidori, 1903.11517]

$^{(*)}$ N.B.: Assuming $\beta_{s\tau} < 0.25$

Leptoquark vector companions

The U_1 leptoquark is a massive vector…

… so it is expected to come along with vector companions



$U^\alpha \sim (\mathbf{3},\mathbf{1})_{2/3}$

$G'^a \sim (\mathbf{8},\mathbf{1})_0$ (heavy “gluon”)

$Z' \sim (\mathbf{1},\mathbf{1})_0$

$$M_U \sim M_{Z'} \sim M_{G'} \sim \mathcal{O}(\mathrm{TeV})$$

As a gauge boson

$$SU(4) \sim \left(\begin{array}{c:c} G'^a & U^\alpha \\ \hdashline (U^\alpha)^* & Z' \end{array}\right)$$

As a quark-lepton bound state

$$G' + Z' \sim \langle \bar{Q}Q \rangle$$

$$U \sim \langle \bar{Q}L \rangle$$

$$Z' \sim \langle \bar{L}L \rangle$$

Other states, e.g. vector-like fermions, are commonly needed

4321 model(s)

$$SU(3)_c = (SU(4)\times SU(3))_{\rm diag}$$

$$U(1)_Y = (SU(4)\times U(1))_{\rm diag}$$

$$\overbrace{\underbrace{\underset{g_4}{SU(4)}\times \underset{g_3}{SU(3)}}_{SU(3)_c}\times SU(2)_L\times \underset{g_1}{U(1)}}^{U(1)_Y} \xrightarrow{SSB} SU(3)_c\times SU(2)_L\times U(1)_Y$$

$$+U_1, G', Z'$$

Why an additional $SU(3)$?

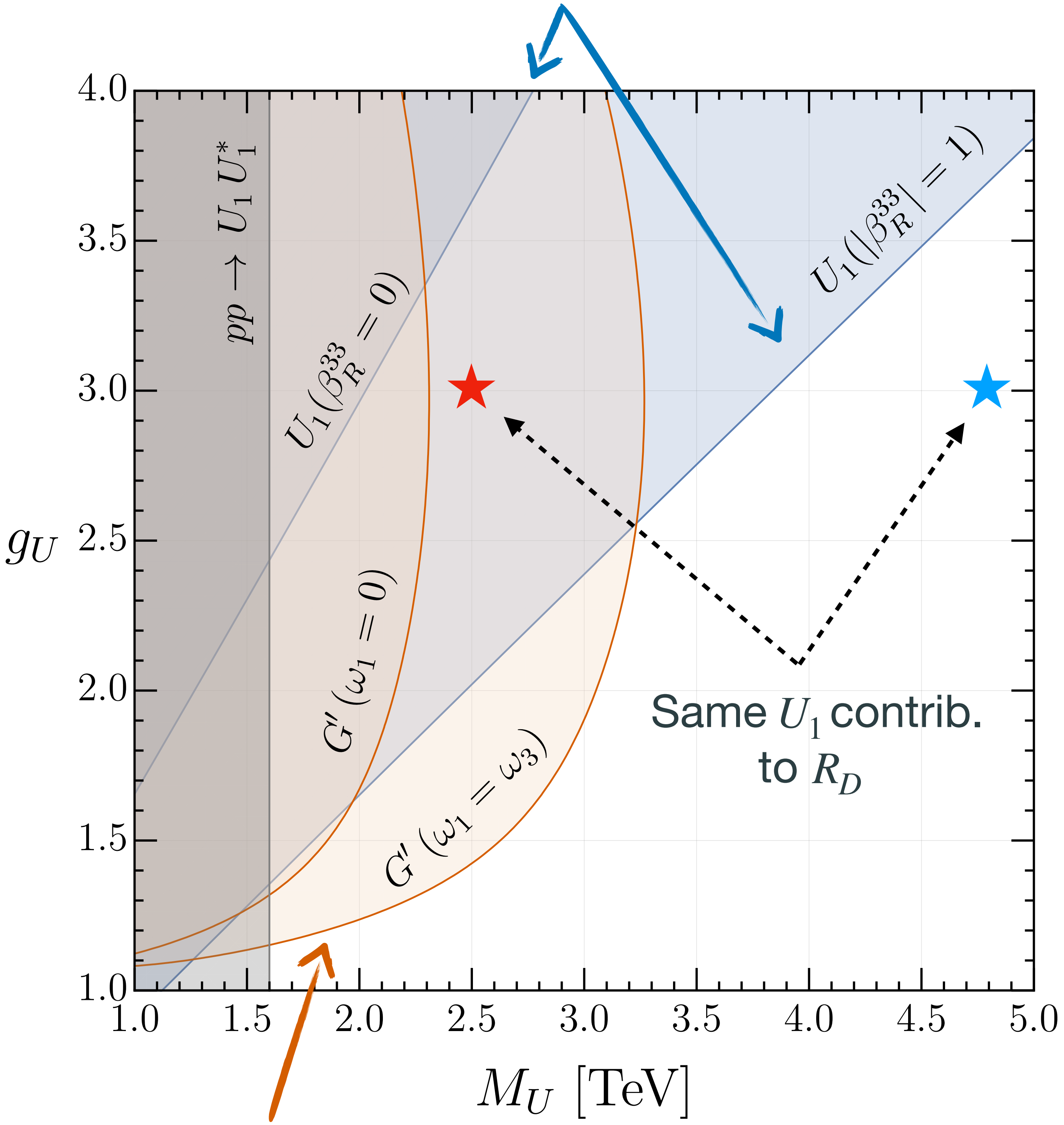
✗ The extra $SU(3)$ gives a G' (color-octet), apart from the unavoidable Z'

✓ It allows to decorrelate the $SU(4)$ from the SM color group. In the limit $g_4 \gg g_{3,1}$

→ $\mathcal{O}(g_3/g_4)$ and $\mathcal{O}(g_1/g_4)$ G' and Z' couplings to valence quarks

High-pT interplay with the new vectors

U_1 from $pp \to \tau\tau$



Same U_1 contrib. to R_D

G' from $pp \to t\bar{t}$

In particular models, the U_1, G' and Z' masses are related

$$M_{G'} = M_U \frac{g_U}{\sqrt{g_U^2 - g_c^2}} \sqrt{\frac{2\omega_3^2}{\omega_1^2 + \omega_3^2}}$$

ω_i : scalar vevs

G' searches are very important for the LH leptoquark ($\beta_R^{33} = 0$)… but not so much for $\beta_R^{33} = 1$

Z' searches typically less relevant

[Baker, JFM, Isidori, König, 1901.10480]

4321… axion!

JFM, Reig, Vicente, 1907.02550

$$SU(3)_c = (SU(4)\times SU(3))_{\text{diag}}$$

$$U(1)_Y = (SU(4)\times U(1))_{\text{diag}}$$

$$\overbrace{\underbrace{\underset{g_4}{SU(4)}\times \underset{g_3}{SU(3)}}_{SU(3)_c}\times SU(2)_L\times \underset{g_1}{U(1)}}^{U(1)_Y} \xrightarrow{SSB} SU(3)_c\times SU(2)_L\times U(1)_Y$$

$$+U_1, G', Z'$$

$$\mathscr{L} = \theta_4\,\frac{\alpha_4}{8\pi}H^A_{\mu\nu}\tilde{H}^{A\,\mu\nu} + \theta_3\,\frac{\alpha_3}{8\pi}C^a_{\mu\nu}\tilde{C}^{a\,\mu\nu}$$

$$\Big\downarrow$$

$$\mathscr{L} = (\theta_4+\theta_3)\,\frac{\alpha_s}{8\pi}G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu}$$

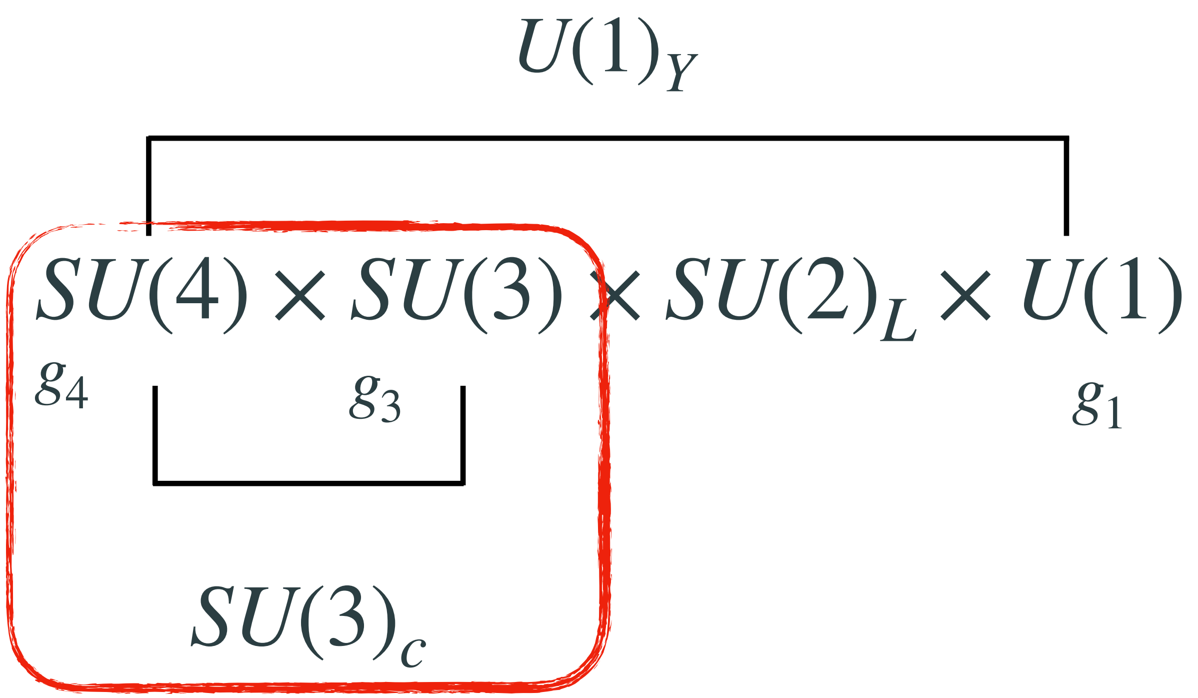
Two axions are necessary to relax the θ_i angles à la Peccei-Quinn

4321… axion!

JFM, Reig, Vicente, 1907.02550

$$SU(3)_c = (SU(4)\times SU(3))_{\rm diag}$$

$$U(1)_Y = (SU(4)\times U(1))_{\rm diag}$$



$U(1)_Y$

$$SU(4)\times SU(3)\times SU(2)_L\times U(1) \xrightarrow{SSB} SU(3)_c\times SU(2)_L\times U(1)_Y$$

g_4 g_3 g_1

$SU(3)_c$

$$+U_1, G', Z'$$

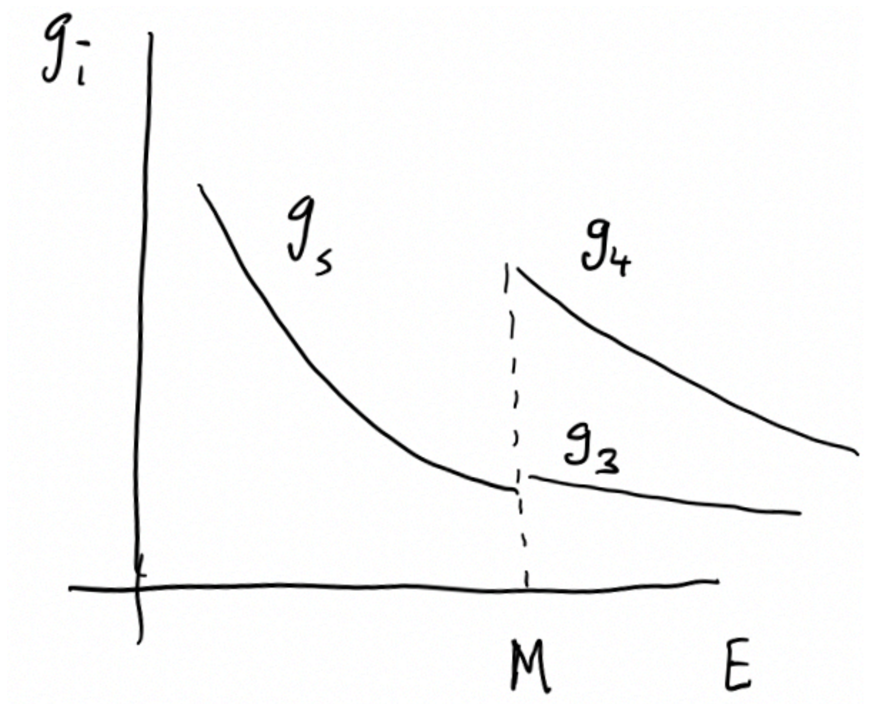
$g_4 \gg g_3$ To avoid Z', G' high-p_T constraints

$$V_{\rm axion} \approx -\Lambda^4_{\rm QCD}\cos\left(\frac{a_1}{f_{a_1}}+\frac{a_2}{f_{a_2}}-\theta_4-\theta_3\right)$$

$$-\Lambda^4_{SU(4)}\cos\left(\frac{a_1}{f_{a_1}}-\theta_4\right)$$

$$-\Lambda^4_{SU(3)}\cos\left(\frac{a_2}{f_{a_2}}-\theta_3\right)$$

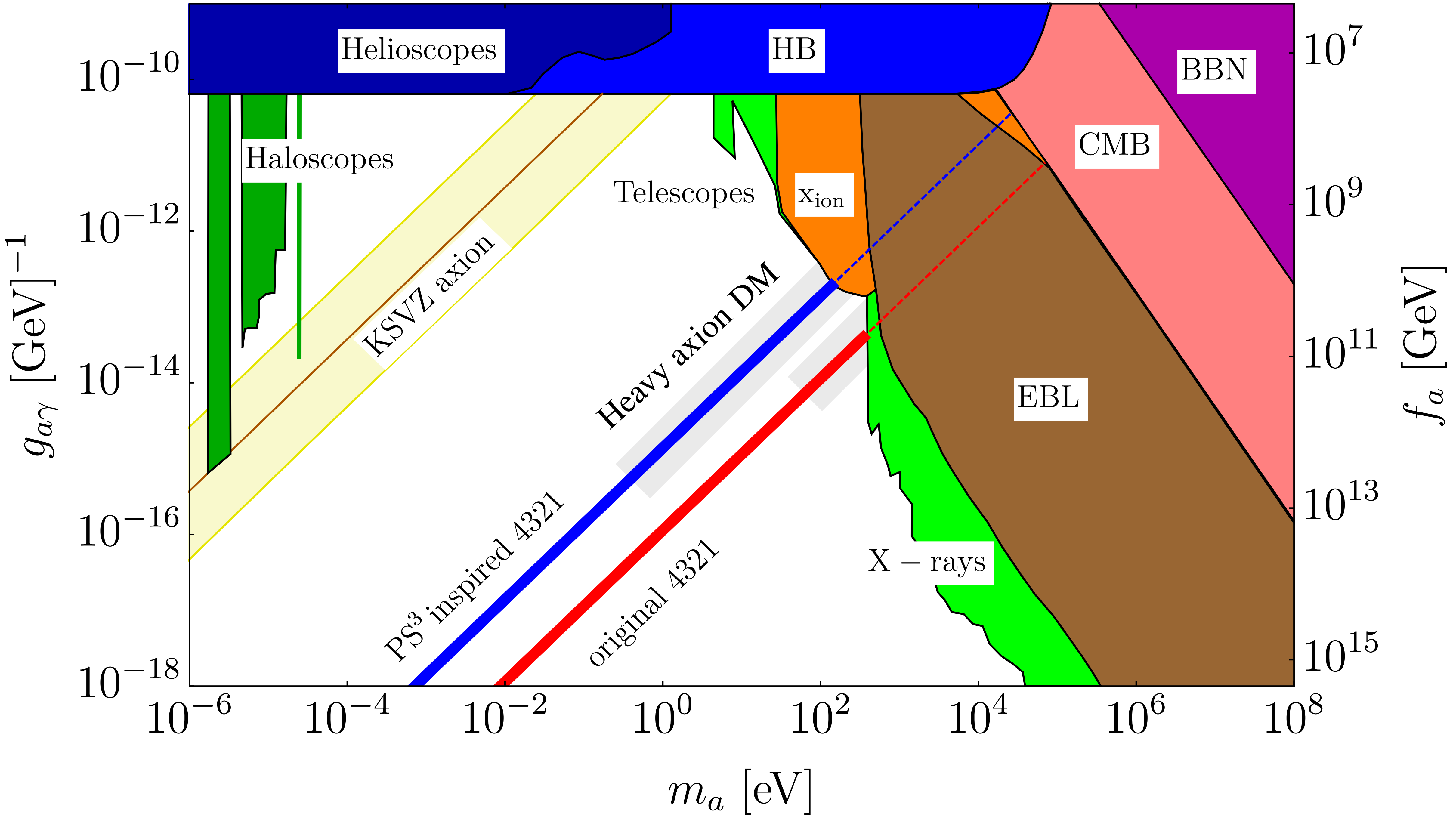
$$\Lambda_{SU(4)} \gg \Lambda_{SU(3),{\rm QCD}}$$



4321… axion!

JFM, Reig, Vicente, 1907.02550

[Astrophysical constraints from Irastorza, Redondo 1801.08127]



Conclusions

Current data is inconclusive and the overall picture may change but…

… it is possible to find well-motivated solutions to the flavor anomalies while remaining consistent with all the other data

Going beyond simplified models is important

→ unexpected experimental signatures and constraints (G', Z', VL fermions,…)

If confirmed, the B-anomalies could change the BSM paradigm

→ The PQ solution of the Strong CP problem is an example. In 4321:

- ★ A new heavy axion is predicted
- ★ (Heavy) axion DM in a region very different from the QCD axion window

Thank you!

Backup slides

More details on 4321 model(s)

$$\overbrace{\underbrace{SU(4)_3 \times}_{SU(3)_c} SU(3)_{1+2} \times SU(2)_L}^{U(1)_Y} \times U(1) \xrightarrow{\langle \Omega_{1,3,15} \rangle} SU(3)_c \times SU(2)_L \times U(1)_Y$$

The original 4321

	Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
$n_{\text{SM-like}} = 3$	$q_L'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
	$u_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$
	$d_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
	$\ell_L'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
	$e_R'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1
$n_{\text{VL}} = 3$	χ_L^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
	χ_R^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
	H	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
	Ω_1	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$
	Ω_3	$\overline{\mathbf{4}}$	$\mathbf{3}$	$\mathbf{1}$	$1/6$
	Ω_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$	0

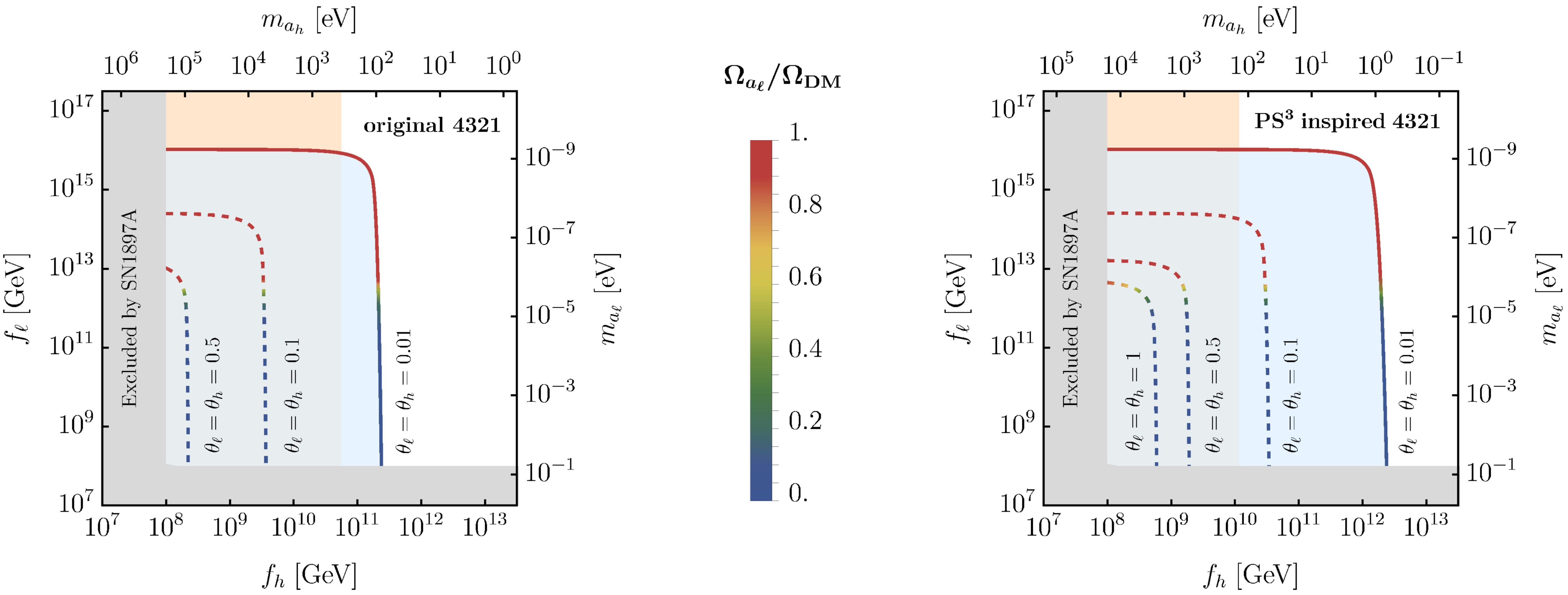
[di Luzio, Greljo, Nardecchia 1708.08450;
di Luzio, JFM, Greljo, Nardecchia, Renner 1808.00942]

PS^3-inspired 4321

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$	
$q_L'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	1st & 2nd families
$u_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	
$d_R'^i$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	
$\ell_L'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	
$e_R'^i$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1	
ψ_L^3	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0	3rd family
$\psi_{R_{u,d}}^3$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$\pm 1/2$	
χ_L^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0	$n_{\text{VL}} = 2$
χ_R^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0	
$H_{1,15}$	$\mathbf{1}, \mathbf{15}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	
Ω_1	$\overline{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$	
Ω_3	$\overline{\mathbf{4}}$	$\mathbf{3}$	$\mathbf{1}$	$1/6$	
Ω_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$	0	

[Bordone, Cornella, JFM, Isidori 1712.01368, 1805.09328;
Greljo, Stefanek, 1802.04274;
Cornella, JFM, Isidori 1903.11517]

Axions Dark Matter

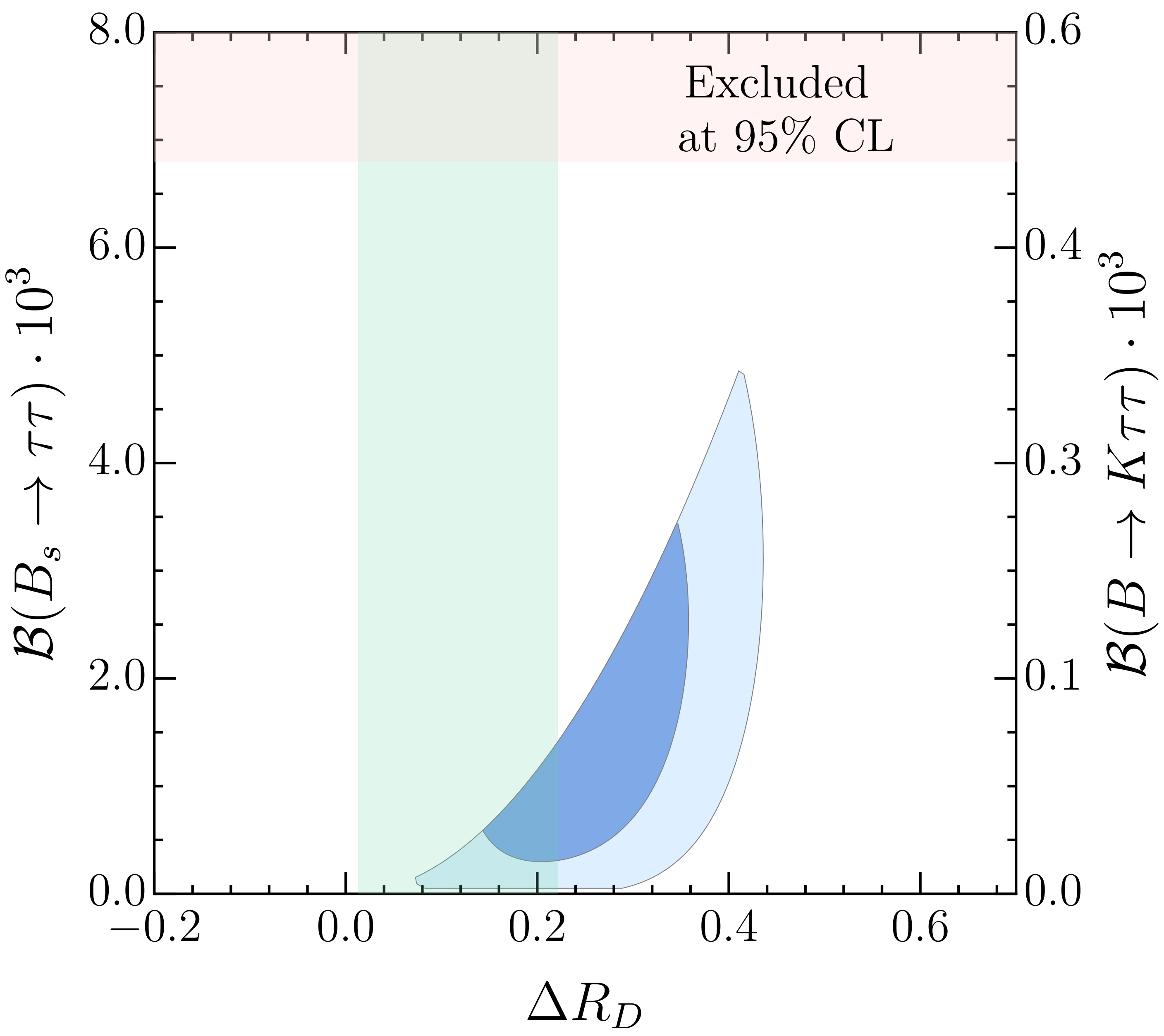


Misalignment mechanism

$T \gg T_c$

$T \sim T_c$

$\mathscr{B}(B_s \to \tau\tau) \quad (\beta^R_{b\tau} = 1)$



The NP enhancement in $\mathscr{B}(B_s \to \tau\tau)$ is huge, about one order of magnitude above the chiral (pure LH) case:

$$\mathscr{B}(B_s \to \tau\tau) \sim \text{few} \cdot 10^{-3}$$

$$\mathscr{B}(B_s \to \tau\tau)_{\text{SM}} = (7.73 \pm 0.49) \cdot 10^{-7}$$

[Bobeth et al. 1311.0903]

→ Exp. limit around the corner

[Cornella, JFM, Isidori, 1903.11517]