B-physics Anomalies: from Data to New Physics Models

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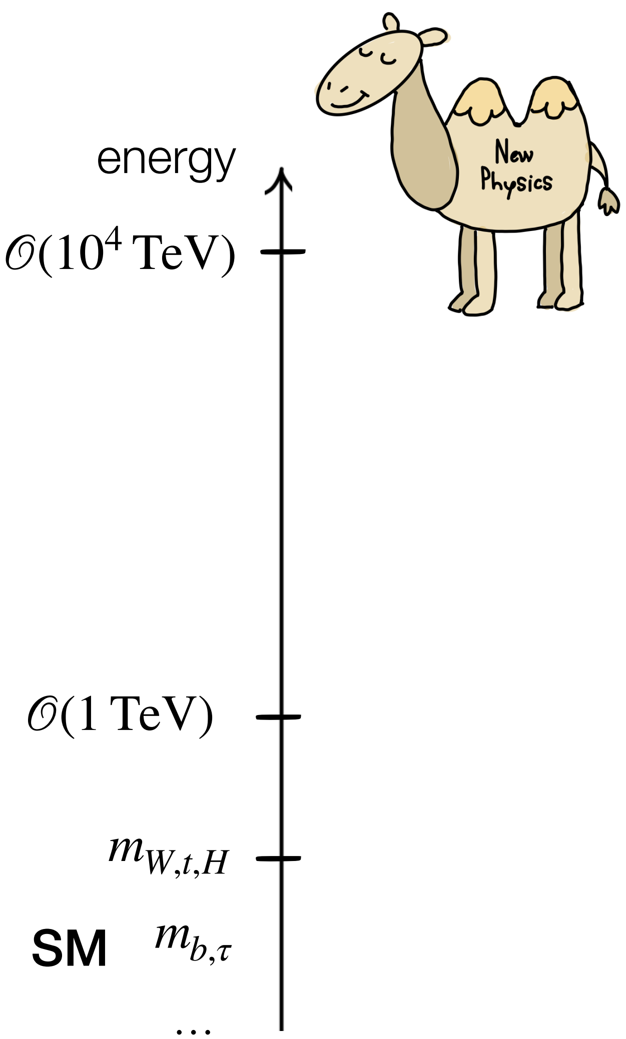
New Physics and Flavor

With a few exceptions, flavor-changing observables agree with the SM.



- If NP has a generic flavor structure, flavor bounds force it to be very heavy: $\bar{K}K\,,\ \mu \to e\gamma \ldots \Rightarrow\ \Lambda > 10^{4-5}\ \mathrm{TeV}$

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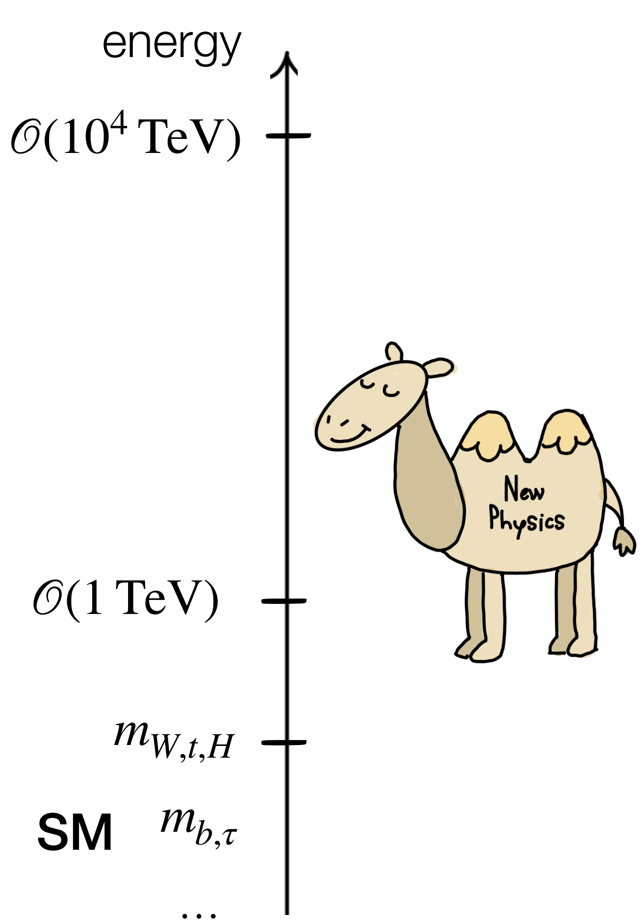

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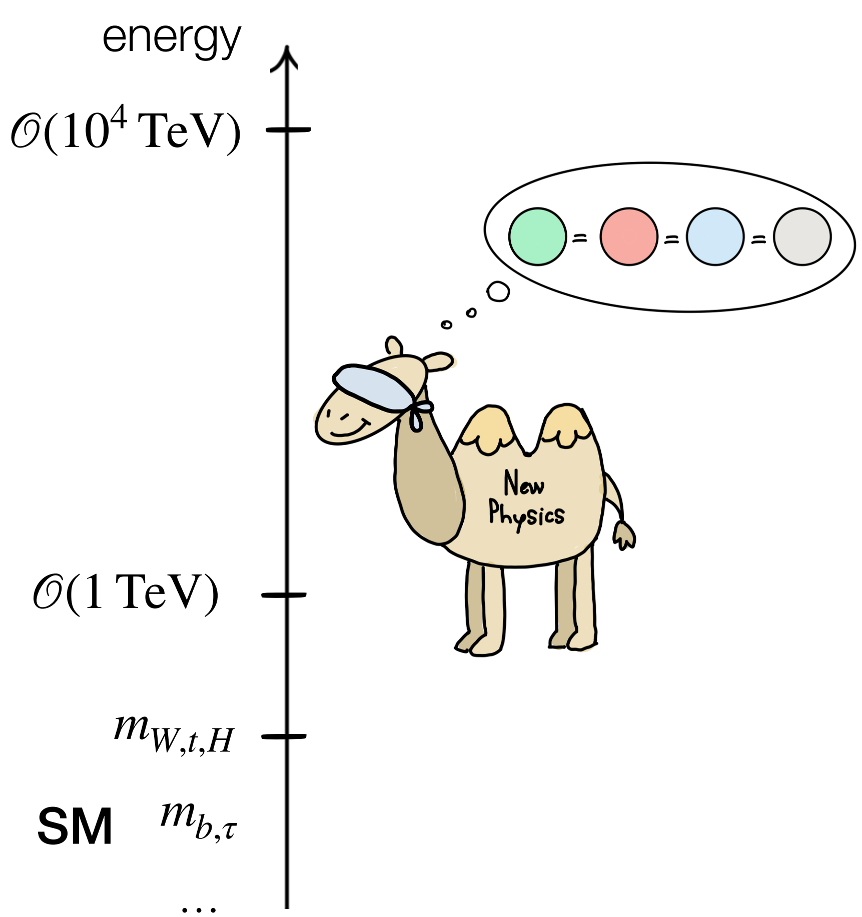

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  e.g. Minimal Flavor Violation:

  Y_{SM} only source of flavor violation (up to $\Lambda \gg 1\mathrm{TeV}$)

  $\rightarrow$ TeV-scale NP is flavor blind

  $\rightarrow$ by construction little to no effects in flavor obs.

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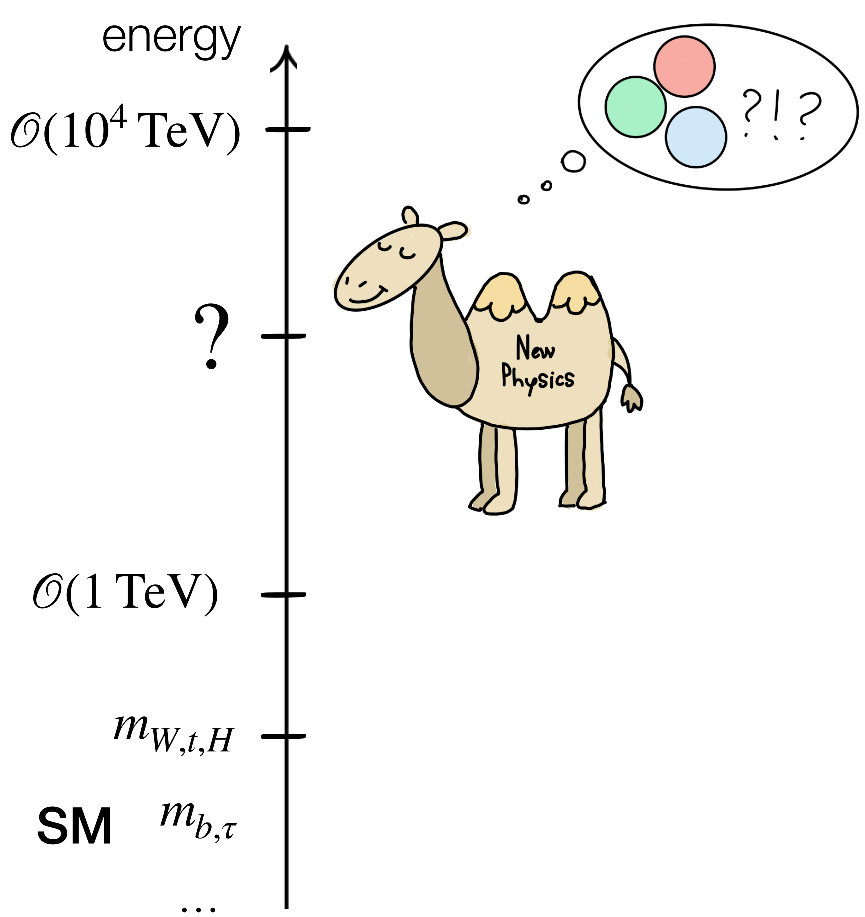

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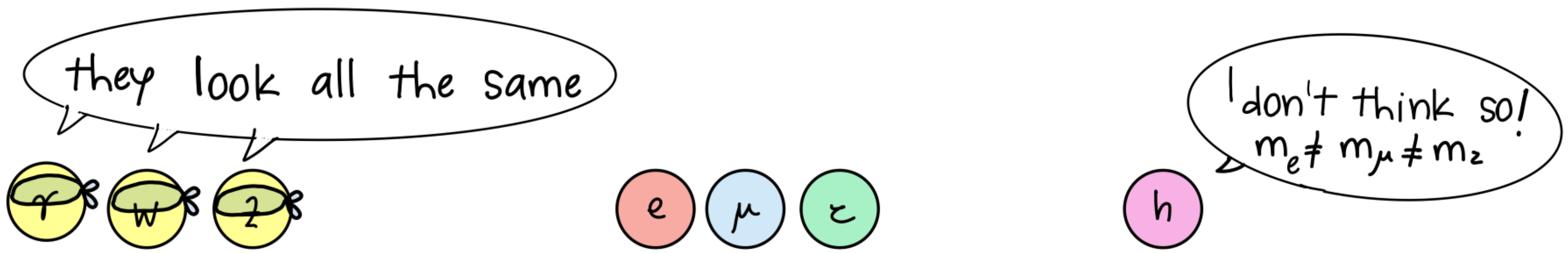
- Now we have hints from flavor, the B anomalies.

  Taking them as genuine BSM signals, what do learn about the scale and flavor structure of New Physics?

Data

The B-physics anomalies

In the SM:



Gauge interactions are lepton-flavor universal.
Lepton masses are the only source of non universality. $\Rightarrow$ $\Gamma_e = \Gamma_\mu = \Gamma_\tau$

(up to kinematical effects)

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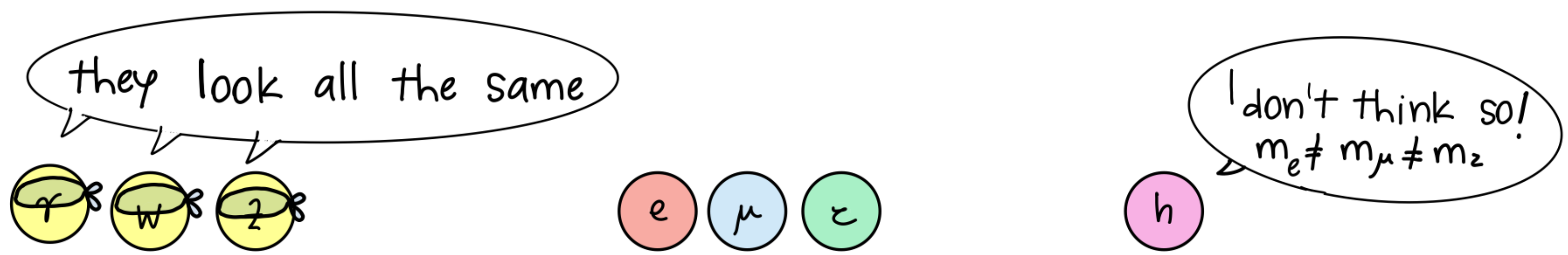

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(up to kinematical effects)

Hints of LFU violation in semi-leptonic B decays:

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

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)} < R_{K^{(*)}}^{\rm SM}$$

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

$\sim 4\,\sigma$

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

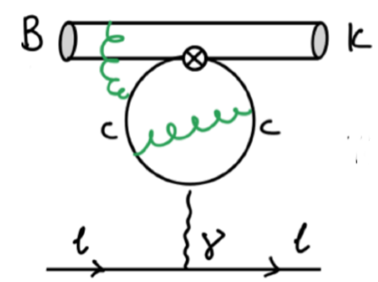
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar\nu)}{\mathcal{B}(B \to D^{(*)}\ell\bar\nu)} > R_{D^{(*)}}^{\rm SM}$$

$\sim 3\,\sigma$

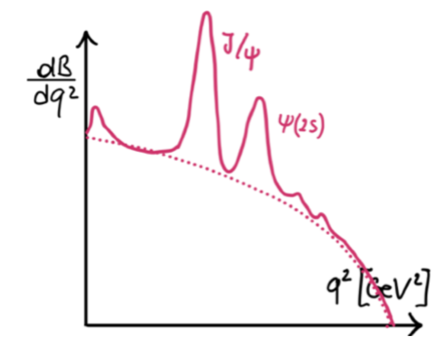
The $b \to sll$ anomalies

"not-so-clean"

- discrepancy in $B \to K^*\mu\mu$ angular distribution
- deficit in $\mathscr{B}(B \to X_s\mu\mu)$ $X_s = K, K^*, \phi$



$\Rightarrow$



- μ/e LFUV in $B \to K^{(*)}ll$
- deficit in $\mathscr{B}(B_s \to \mu\mu)$

"clean"

$R_{K^{(*)}}^{[1.1,6]\ \mathrm{GeV}^2} = 1.00 \pm 0.01$ [Bordone et al, 1605.07633]

$\mathscr{B}(B_s \to \mu\mu)_{\mathrm{SM}} = (3.66 \pm 0.14) \times 10^{-9}$

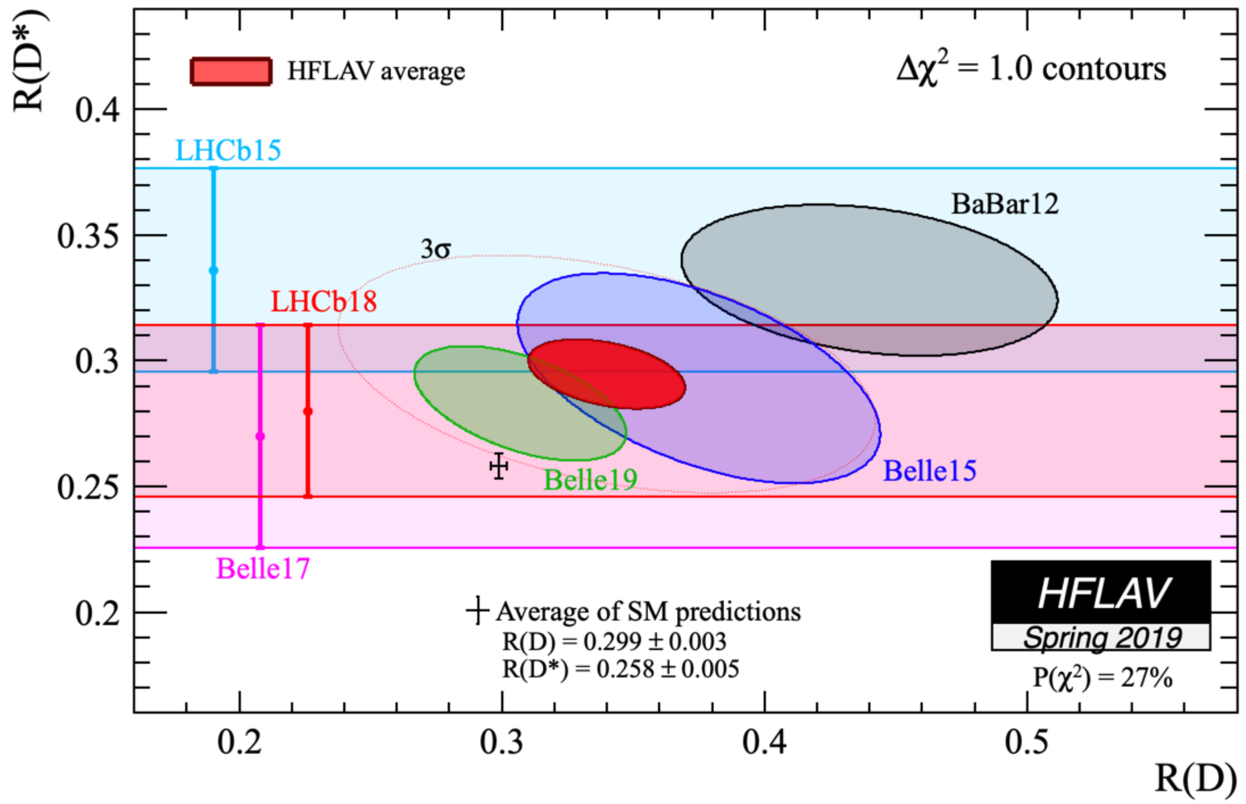
[Beneke et al., 1908.07011]

LHCb results on LFU ratios **this year**: $R_K^{[1.1,6]}$ update ($3.1\,\sigma$) [LHCb, 2103.11769]

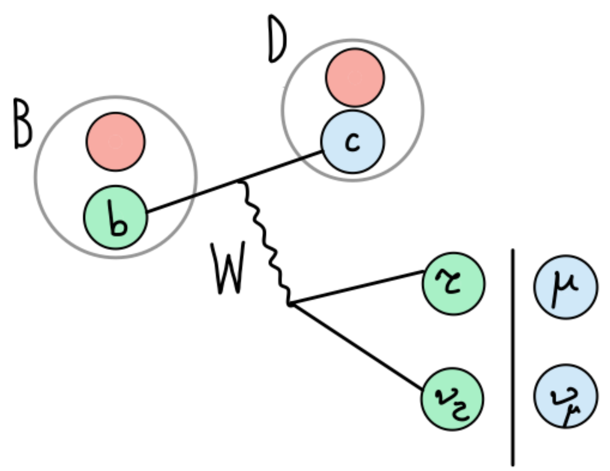
first results for R_{K_s} and $R_{K^{*+}}$ [LHCb, 2110.09501]

Global significance for New Physics in $b \to sll$ $\sim 4\,\sigma$ [Isidori, Lancierini, Owen, Serra, 2104.05631]

The $b \to c l \nu$ anomalies



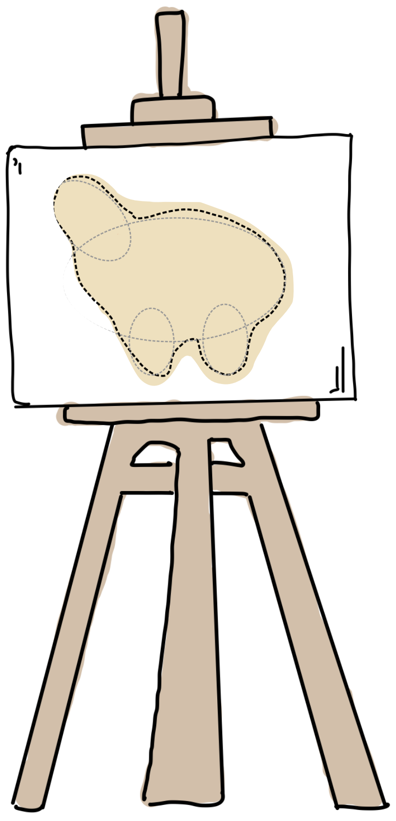
$$R_{D^{(*)}} = \frac{\mathscr{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathscr{B}(B \to D^{(*)}\ell\bar{\nu})}$$



- $\sim 15\,\%$ enhancement due to excess in tau mode
- theoretically clean
- measurements by Babar, Belle, LHCb (so far R_{D^*} only) in good agreement
- $3.1\,\sigma$ tension (combined)

Lower significance, need experimental clarification.

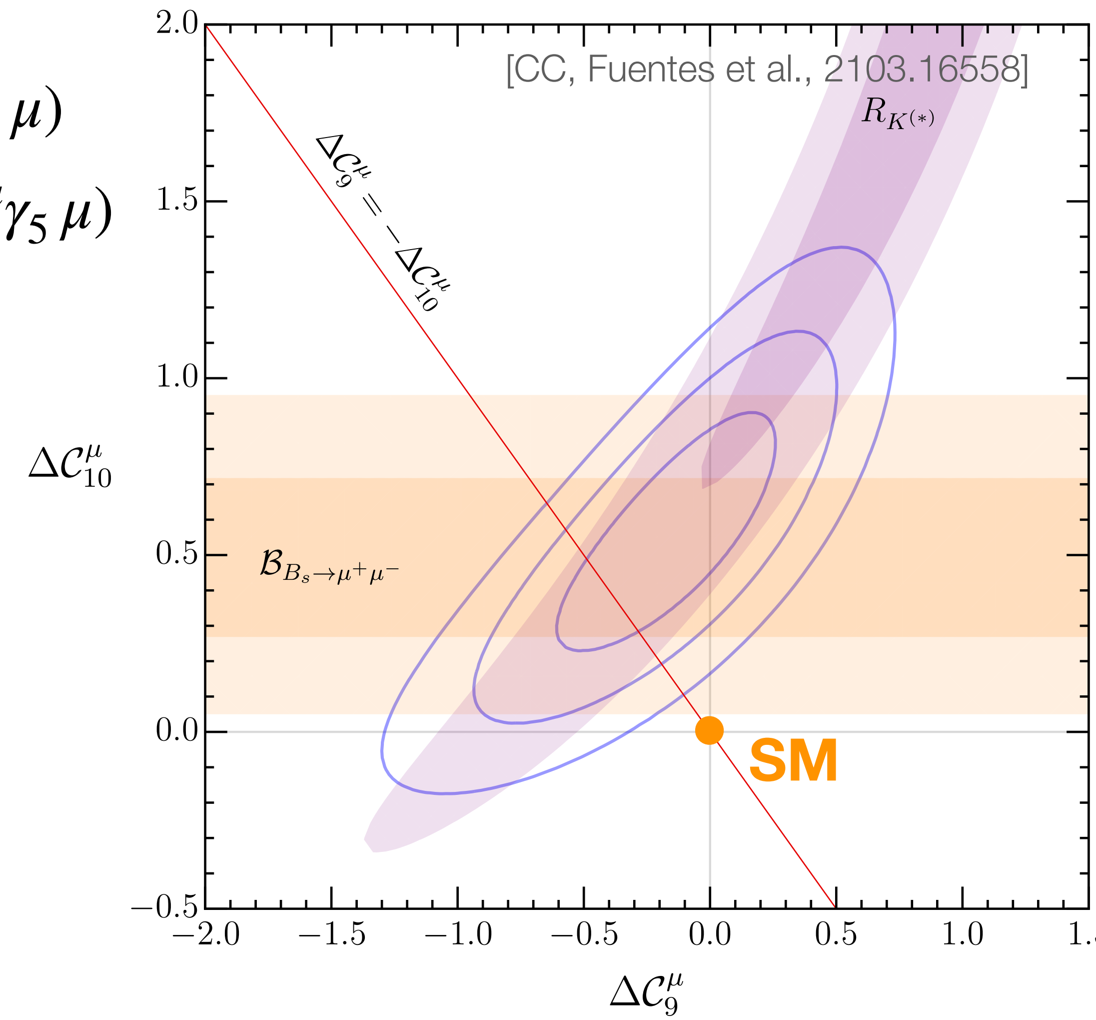
NP interpretation (I): Effective Theory



EFT for $b \to sll$

$$\mathscr{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{\alpha}{4\pi} \sum_i C_i O_i$$

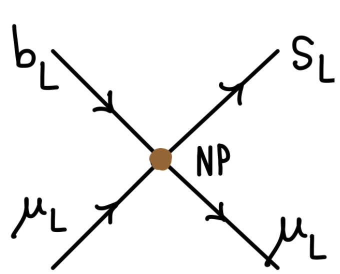
$$O_9^\mu = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \mu)$$
$$O_{10}^\mu = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$



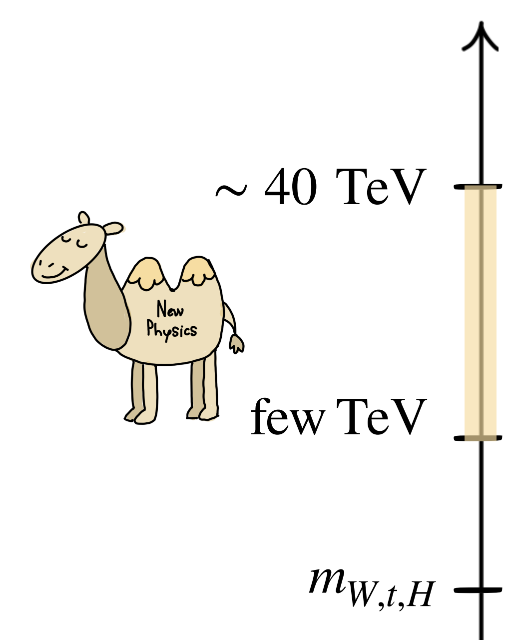
- NP in C_9^μ only
- left-handed LFUV NP + subleading LFU shift
  $\Delta C_9^\mu = -\Delta C_{10}^\mu$ $\qquad$ ΔC_9^U

clean obs. only	$4.6\,\sigma$
all obs., marginalizing in ΔC_9^U	$4.8\,\sigma$
all obs. + estimate of $c\bar{c}$ loop	$\gg 5\sigma$

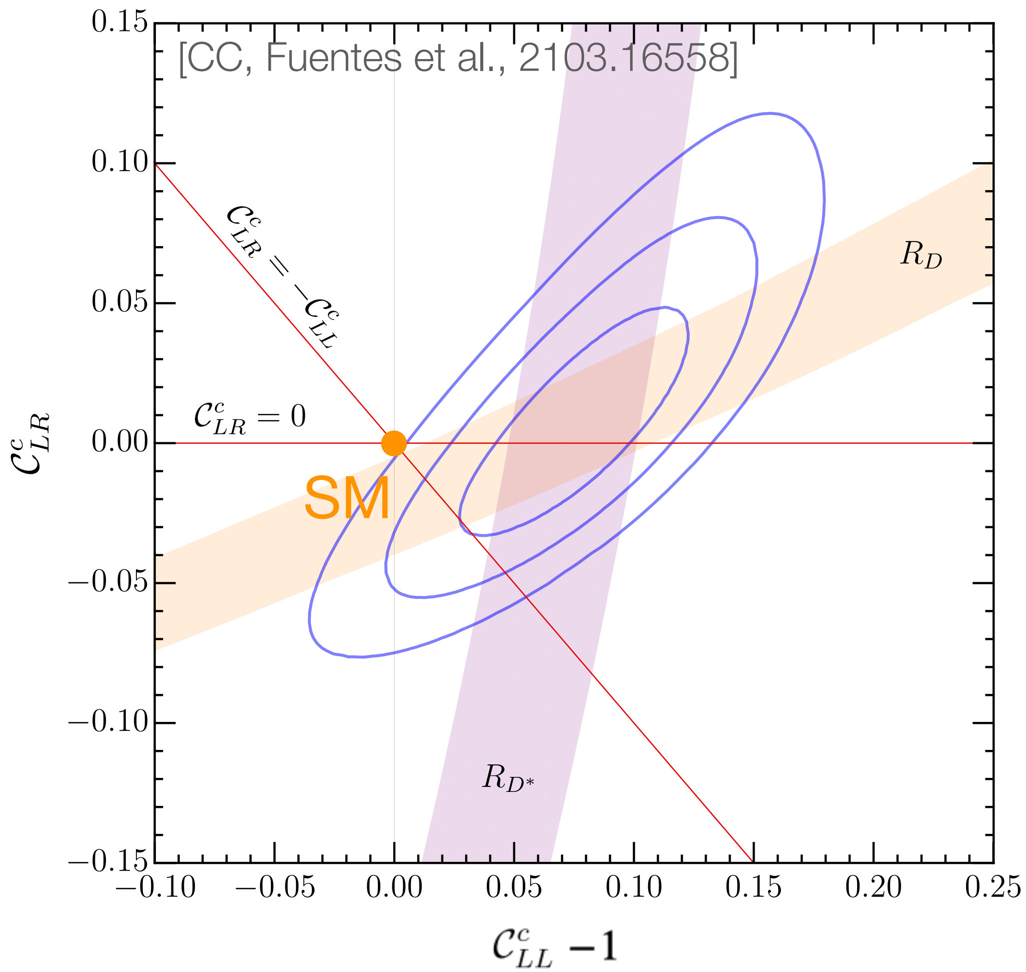
[2103.13370, 2104.0892. 2104.10058...]



$$\sim 4 \times 10^{-5}\ G_F \quad \Rightarrow \quad \frac{g_{\text{NP}}^2}{\Lambda^2} \sim \frac{1}{(40\ \text{TeV})^2}$$



EFT for $b \to c\tau\nu$

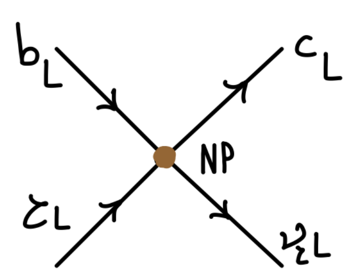


$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{cb} \sum_i C_i O_i$$

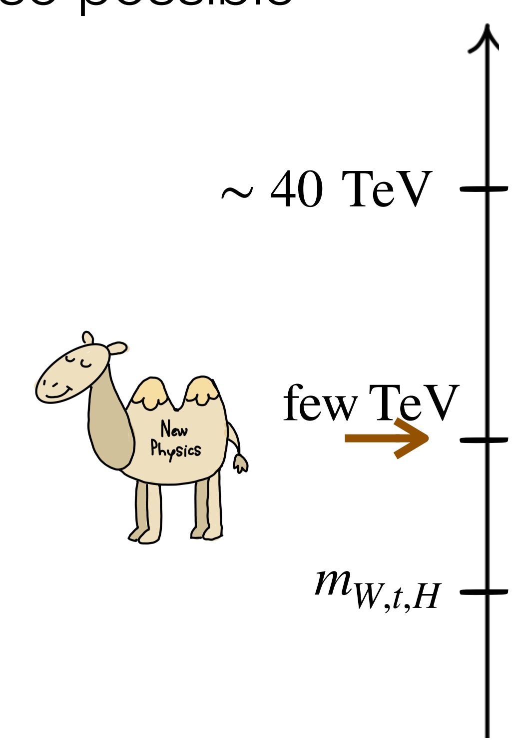
$$O^i_{LL} = (\bar{u}^i_L \gamma_\mu \nu_L)(\bar{\tau}_L \gamma^\mu b_L) \qquad C^{\text{SM}}_{LL} = 1$$

$$O^i_{LR} = (\bar{u}^i_L \gamma_\mu \nu_L)(\bar{\tau}_R \gamma^\mu b_R) \qquad C^{\text{SM}}_{LR} = 0$$

- left-handed NP (=Fermi interaction!)
- other structures also possible



$\sim 10^{-2}\, G_F$



Why both?

No obvious connection. Why combine both anomalies in a single NP framework?

$$\begin{array}{ccc} b \to sll & & b \to cl\nu \\ (\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L) & \xleftrightarrow{SU(2)_L} & (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L) \end{array}$$

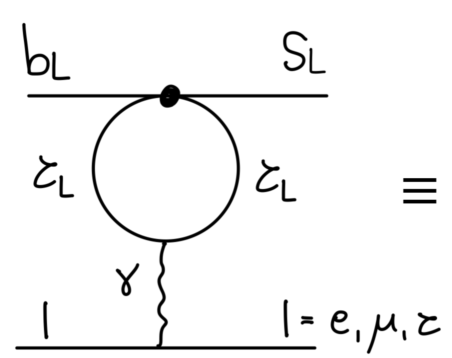
⇒ Minimal sol: **left-handed NP in semi-leptonic operators** (RH currents also possible)

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

$$b \to s\nu\bar{\nu} \to \quad C^{(3)}_{\ell q} \approx C^{(1)}_{\ell q} \equiv C_{LL}$$

Connection between anomalies:

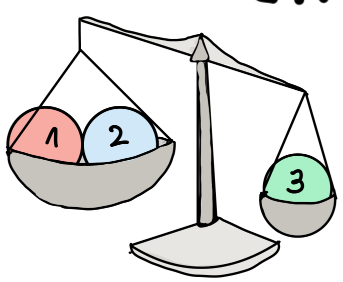
$$R_{D^{(*)}} \;\Rightarrow\; b_L \to c_L \tau_L \nu_L \;\overset{SU(2)_L}{\sim}\; b_L \to s_L \tau_L \tau_L \;\overset{\text{RGE}}{\Rightarrow}$$



$$\equiv \Delta C_9^U$$

Why both?

FLAVOR HIERARCHIES



standard LFUV

$$y_3 \gg y_2 \gg y_1$$

?

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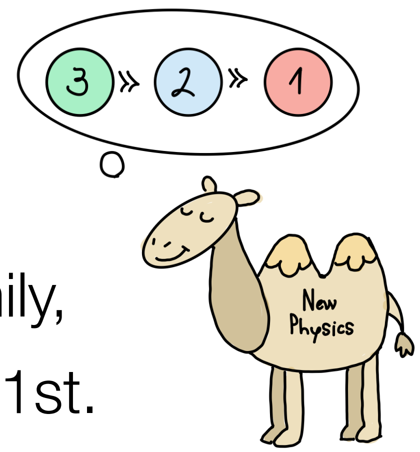
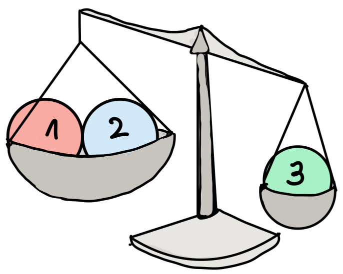


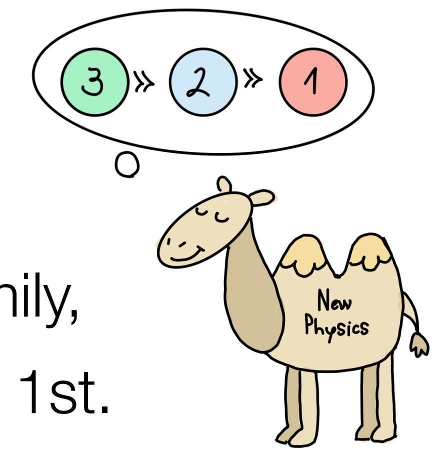
non-standard LFUV

NP couples mostly to 3rd family, smaller couplings to 2nd and 1st.

Why both?



FLAVOR HIERARCHIES $\overset{?}{\longleftrightarrow}$ **FLAVOR ANOMALIES**



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NP couples mostly to 3rd family,

smaller couplings to 2nd and 1st.

$$U(2)^5 = U(2)_q \times U(2)_l \times U(2)_u \times U(2)_d \times U(2)_e$$

$$\psi = (\,\psi_1 \ \psi_2 \ \psi_3\,)$$

Why both?

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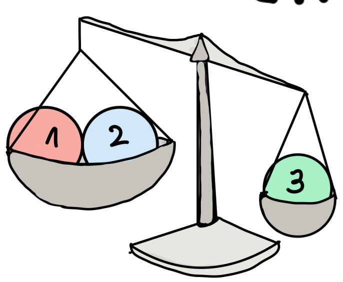

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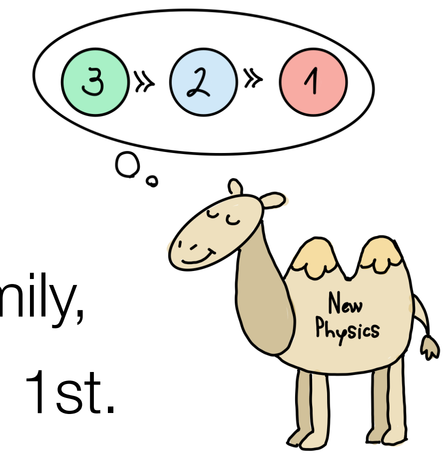

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$$\psi = (\,(\psi_1\ \psi_2)\ \psi_3\,)$$

SM masses & mixings, “flavored”
alternative to MFV [Barbieri et al.,1105.3396]

$$Y = y_3 \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

exact U(2)^5

$$Y = y_3 \begin{bmatrix} \Delta & V \\ 0 & 1 \end{bmatrix}$$

minimally broken U(2)^5

$$|V_q| = \epsilon_q = \mathcal{O}(y_t |V_{ts}|) \quad |\Delta_{u,d,e}| \sim y_{c,s,\mu}$$

Why both?

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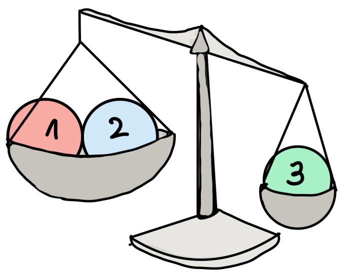

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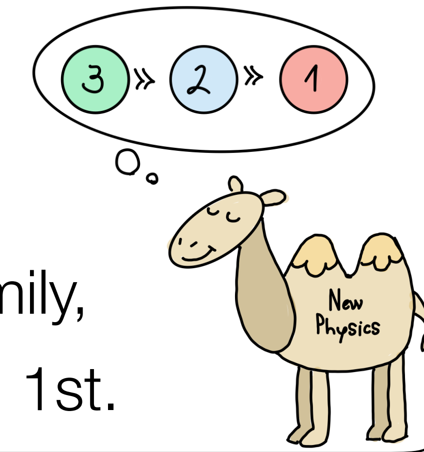

NP couples mostly to 3rd family, smaller couplings to 2nd and 1st.

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SM masses & mixings, “flavored” alternative to MFV [Barbieri et al.,1105.3396]

Same pattern? [Barbieri et al.,1512.01560]

$$Y = y_3 \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

exact U(2)⁵

NP coupled only to 3rd family

$$Y = y_3 \begin{bmatrix} \Delta & V \\ 0 & 1 \end{bmatrix}$$

minimally broken U(2)⁵

NP max for 3rd family, suppressed by ϵ_q (ϵ_l) for each 2nd family quark (lepton)

$$|V_q| = \epsilon_q = \mathcal{O}(y_t |V_{ts}|) \quad |\Delta_{u,d,e}| \sim y_{c,s,\mu}$$

EFT for combined explanations (LL)

$$\mathscr{L}_{\rm EFT}^{\rm NP} = -\frac{2}{v^2} C_{LL}^{ij\alpha\beta} \left(\bar{q}_L^i \gamma^\mu l_L^\alpha\right)\left(\bar{l}_L^\beta \gamma_\mu q_L^j\right)$$

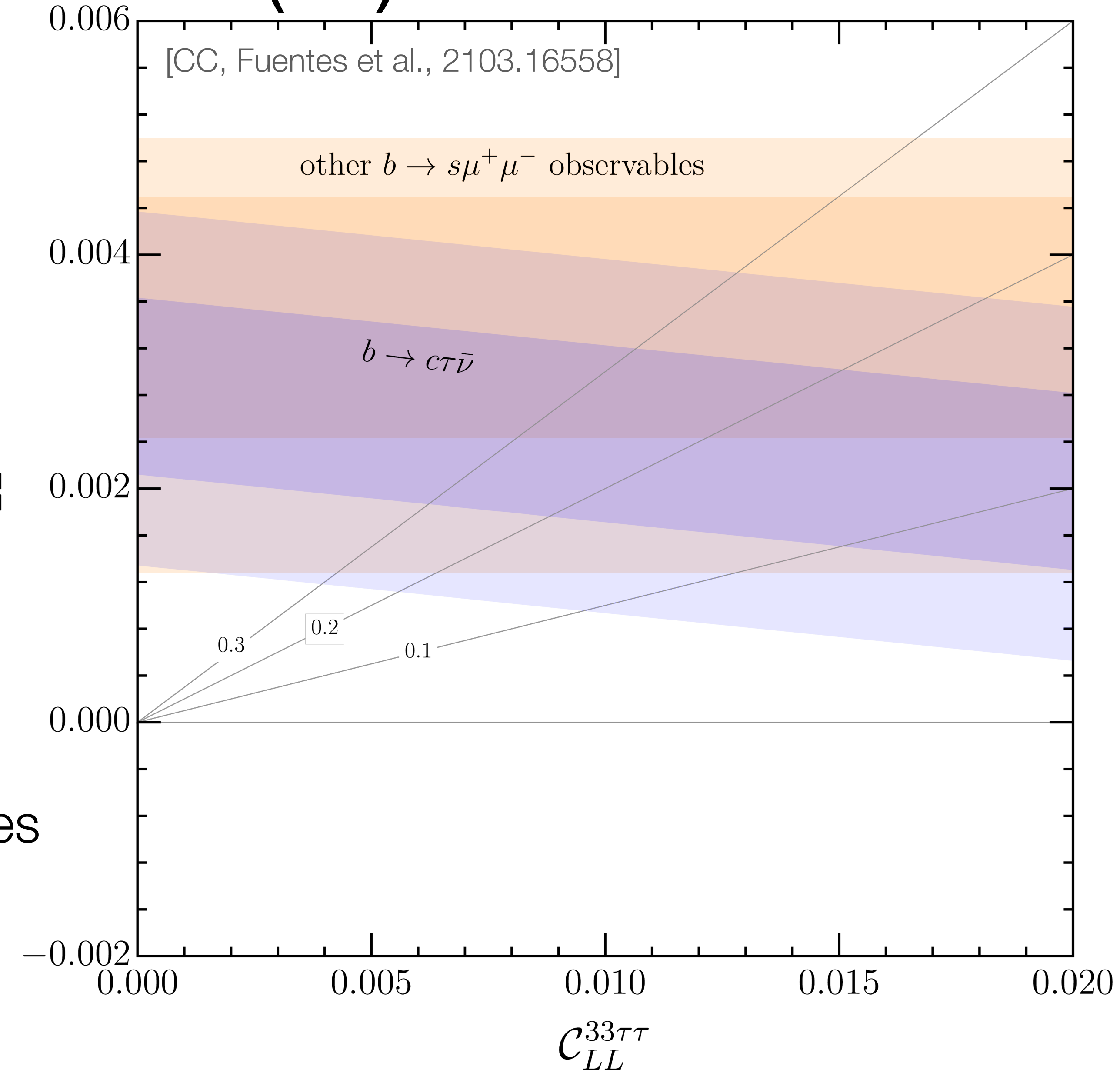
- Data support U(2) scaling,

$b \to c$: $C_{LL}^{33\tau\tau} \sim 0.1$, $C_{LL}^{23\tau\tau} \sim \epsilon_q C_{LL}^{33\tau\tau}$

$b \to s$: $C_{LL}^{23\tau\tau} \sim \epsilon_q C_{LL}^{33\tau\tau}$, $C_{LL}^{23\mu\mu} \sim \epsilon_q \epsilon_l^2 C_{LL}^{33\tau\tau}$

$\epsilon_q, \epsilon_l \sim 0.1$

- good consistency between the anomalies



$$\frac{R_{D^{(*)}}}{R_{D^{(*)}}^{\rm SM}} - 1 = 2{\rm Re}\left(C_{LL}^{33\tau\tau} + \frac{V_{cs}}{V_{cb}} C_{LL}^{23\tau\tau}\right)$$

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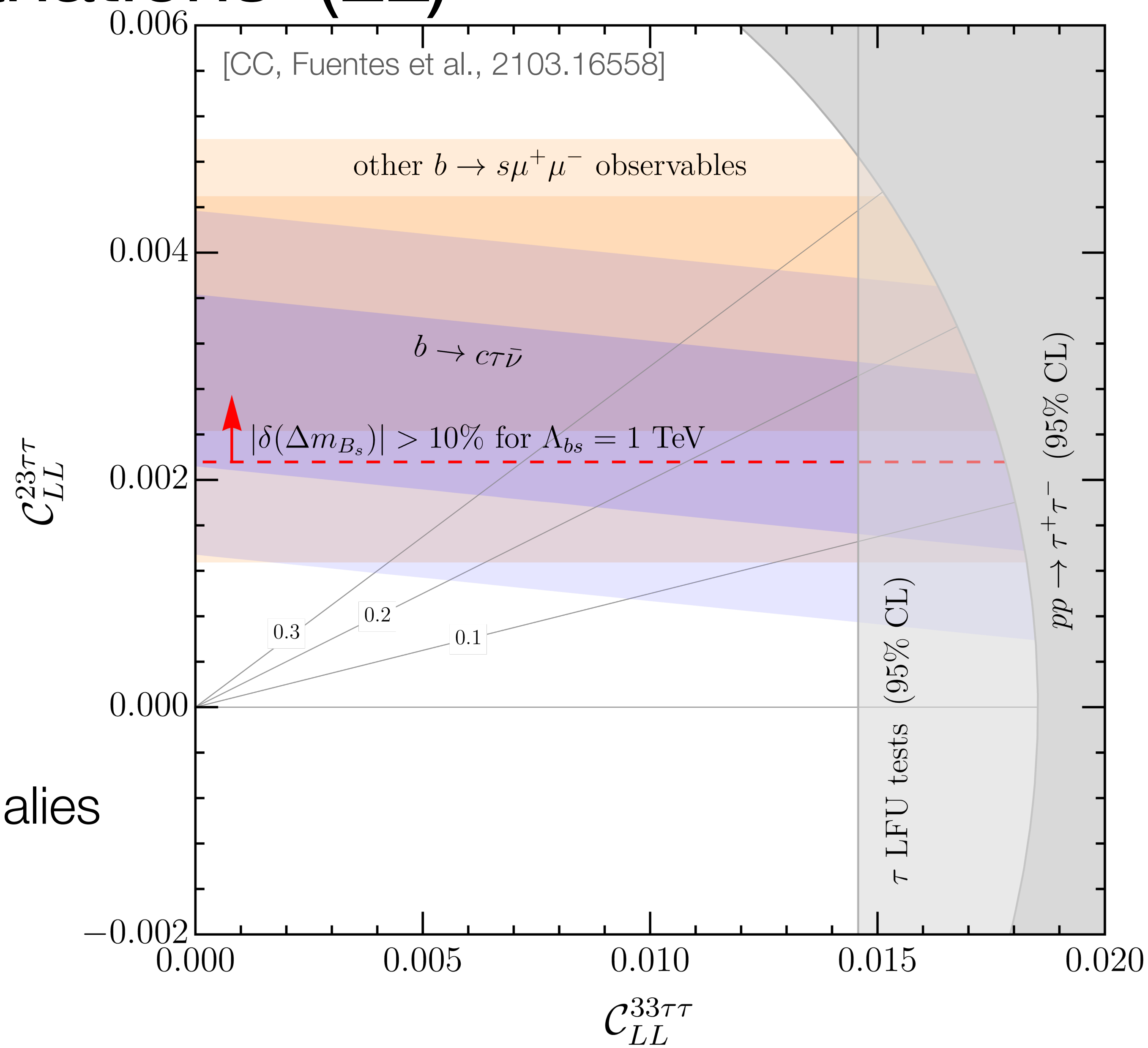
- Data support U(2) scaling,

$b \to c$ $\quad$ $b \to s$

$$C_{LL}^{33\tau\tau} \sim 0.1$$

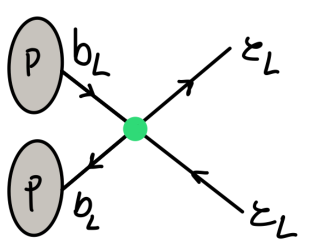
$$C_{LL}^{23\tau\tau} \sim \epsilon_q C_{LL}^{33\tau\tau} \qquad \epsilon_q, \epsilon_l \sim 0.1$$

$$C_{LL}^{23\mu\mu} \sim \epsilon_q \epsilon_l^2 C_{LL}^{33\tau\tau}$$

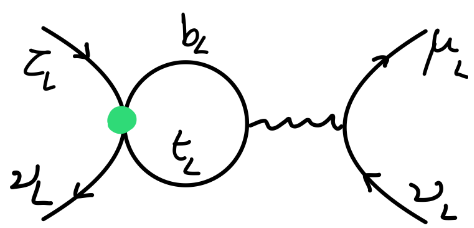


- good consistency between the anomalies

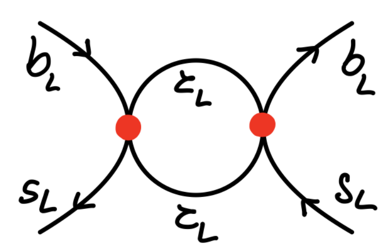
- several constraints (driven by $R_{D^{(*)}}$)



$pp \to \tau\tau$



τ LFU tests



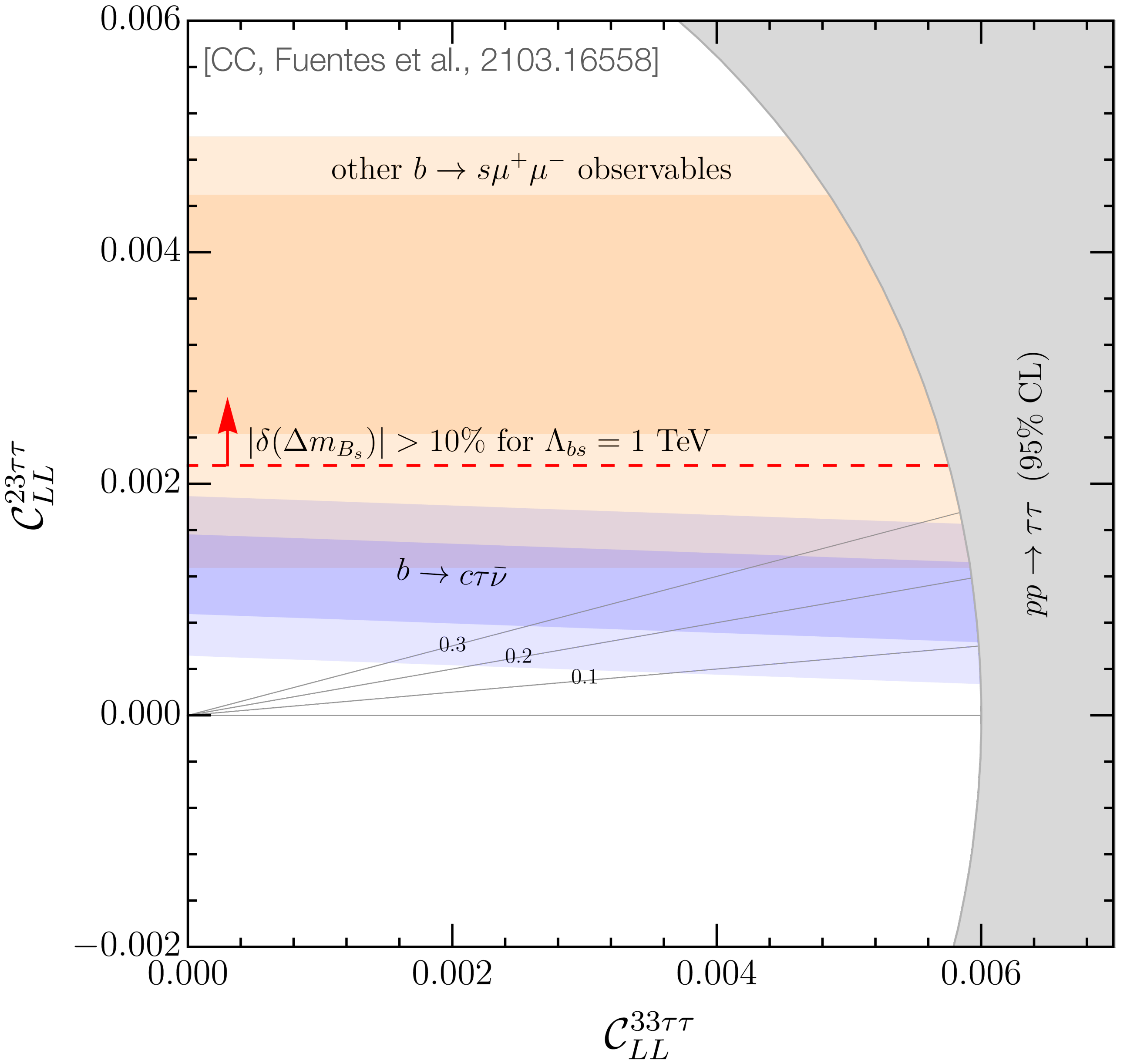
$B_s - \bar{B}_s$

$$\frac{R_{D^{(*)}}}{R_{D^{(*)}}^{\rm SM}} - 1 = 2{\rm Re}\left(C_{LL}^{33\tau\tau} + \frac{V_{cs}}{V_{cb}} C_{LL}^{23\tau\tau}\right)$$

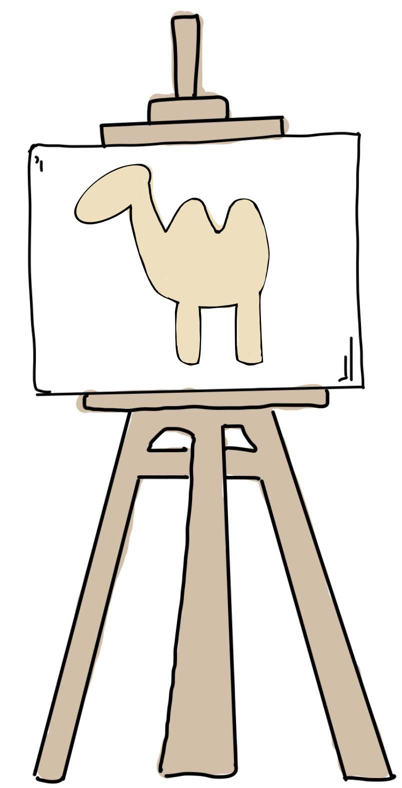
EFT for combined explanations (LL + LR)

$$\mathcal{L}_{\rm EFT}^{\rm NP} = -\frac{2}{v^2}\left[C_{LL}^{ij\alpha\beta}\,(\bar{q}_L^i\gamma^\mu l_L^\alpha)(\bar{l}_L^\beta\gamma_\mu q_L^j) + \left(C_{LR}^{ij\alpha\beta}\,(\bar{q}_L^i\gamma_\mu \ell_L^\alpha)(\bar{e}_R^\beta\gamma^\mu d_R^j) + \mathrm{h.c.}\right) + C_{RR}^{ij\alpha\beta}\,(\bar{d}_R^i\gamma_\mu e_R^\alpha)(\bar{e}_R^\beta\gamma^\mu d_R^j)\right]$$

- LR helps saturating $R_{D^{(*)}}$
  - $\rightarrow$ τ LFU and B_s-$\bar{B}_s$ less stringent.
- Both chiralities enter $pp \rightarrow \tau\tau$
  - $\rightarrow$ stronger high-p_T bounds.



NP interpretation (II): the U_1 simplified model



Which mediator?

- Only leptoquarks (scalars & vectors) are viable tree-level mediators

  ✓ no 4-lepton and 4-quark processes at tree level

  ✓ no resonant production in quark-quark initiated processes

- Three possibilities for a combined explanation:
  - $S_1 + S_3$ [Crivellin et al 1703.09226; Buttazzo et al. 1706.07808; Marzocca 1803.10972...]
  - $R_2 + S_3$ [Bečirević et al., 1806.05689]
  - $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$ [di Luzio et al., 1708.08450; Calibbi et al., 1709.00692; Bordone, CC, et al. 1712.01368; Barbieri, Tesi 1712.06844; Heck,Teresi 1808.07492…]

  ✓ no $b \to s\nu\bar{\nu}$ at tree level

Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_3 $(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	✓	✗	✗
S_1 $(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✗	✓	✗
R_2 $(\mathbf{3}, \mathbf{2}, 7/6)$	✗	✓	✗
U_1 $(\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓
U_3 $(\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗	✗

[Sumensari et al., 2103.12504]

The U_1 simplified model

$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta_L^{i\alpha} (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) + \beta_R^{i\alpha} (\bar{d}_R^i \gamma_\mu e_R^\alpha)\right] + \mathrm{h.c.} \qquad U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$$

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

$\tau \to \mu\gamma$ [loop]

$R_{K^{(*)}}$

$R_{D^{(*)}}$

$b \to s\tau\mu$ [tree]

$b \to s\tau\tau$ [tree]

$\beta^L_{b\tau} = 1$

$\beta^R_{b\tau} \sim \mathcal{O}(1)$

$\beta^L_{s\tau}, \beta^L_{b\mu} \sim \mathcal{O}(0.1)$

$\beta^L_{s\mu}, \beta^L_{d\tau} \sim \mathcal{O}(0.01)$

Benchmarks:

1. $\beta^R_{b\tau} = 0$
2. $|\beta^R_{b\tau}| = |\beta^L_{b\tau}| = 1$ [models with 3rd family quark-lepton unification]

✓ Good description of all low-energy data with U(2)-like flavor structure.

The U_1 simplified model

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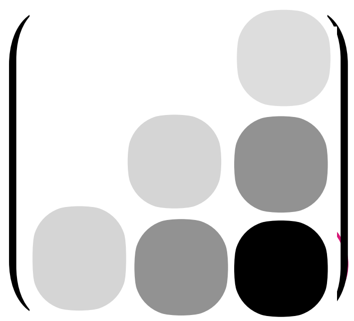
$\beta^L =$ 

$\tau \to \mu\gamma$ [loop]

$R_{K^{(*)}}$ $R_{D^{(*)}}$ $b \to s\tau\mu$ [tree]

$b \to s\tau\tau$ [tree]

$$\beta^R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta_{b\tau}^R \end{pmatrix}$$

$\beta_{b\tau}^L = 1$

$\beta_{b\tau}^R \sim \mathcal{O}(1)$

$\beta_{s\tau}^L, \beta_{b\mu}^L \sim \mathcal{O}(0.1)$

$\beta_{s\mu}^L, \beta_{d\tau}^L \sim \mathcal{O}(0.01)$

Benchmarks:

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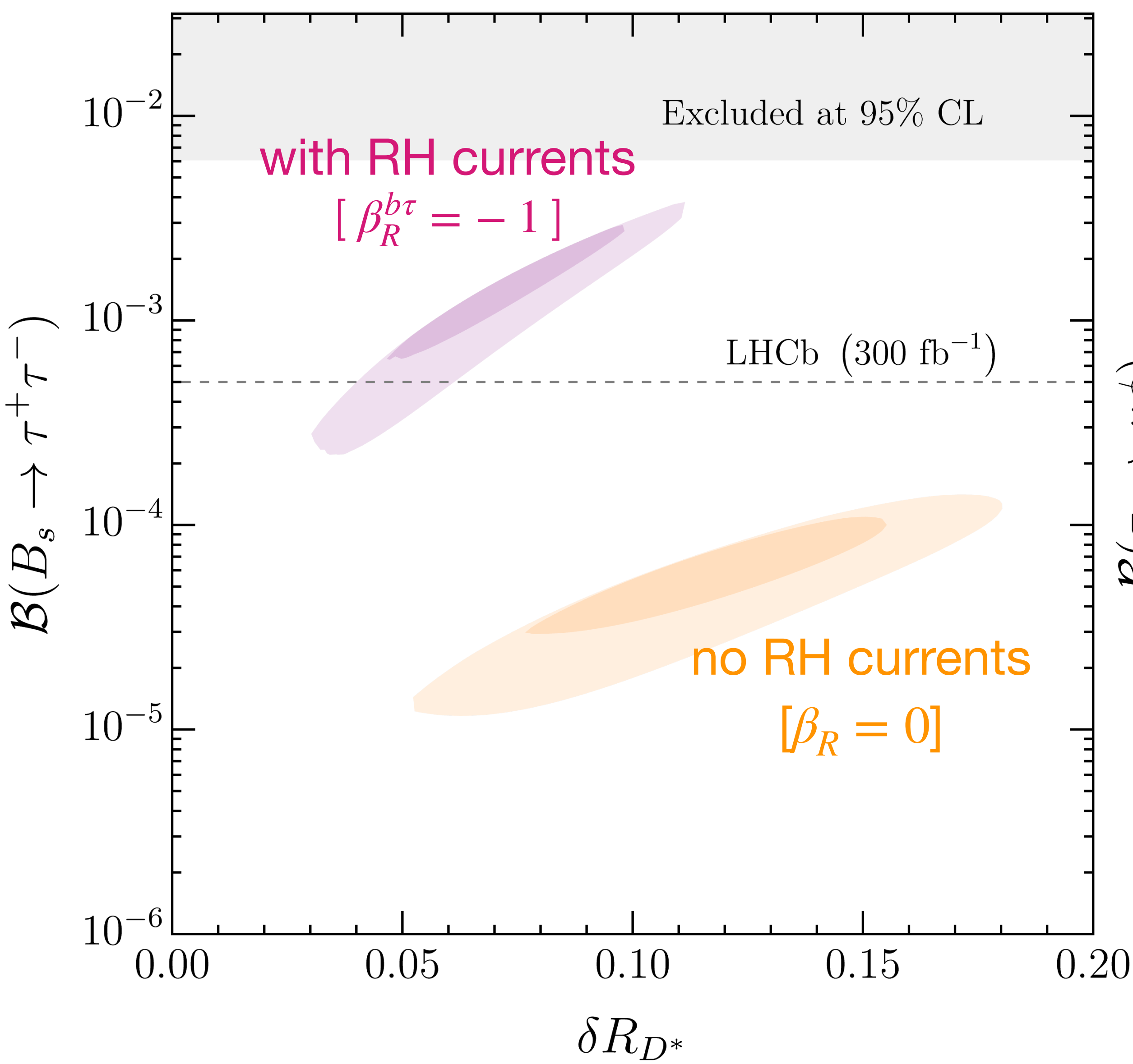
2. $|\beta_{b\tau}^R| = |\beta_{b\tau}^L| = 1$ [models with 3rd family quark-lepton unification]

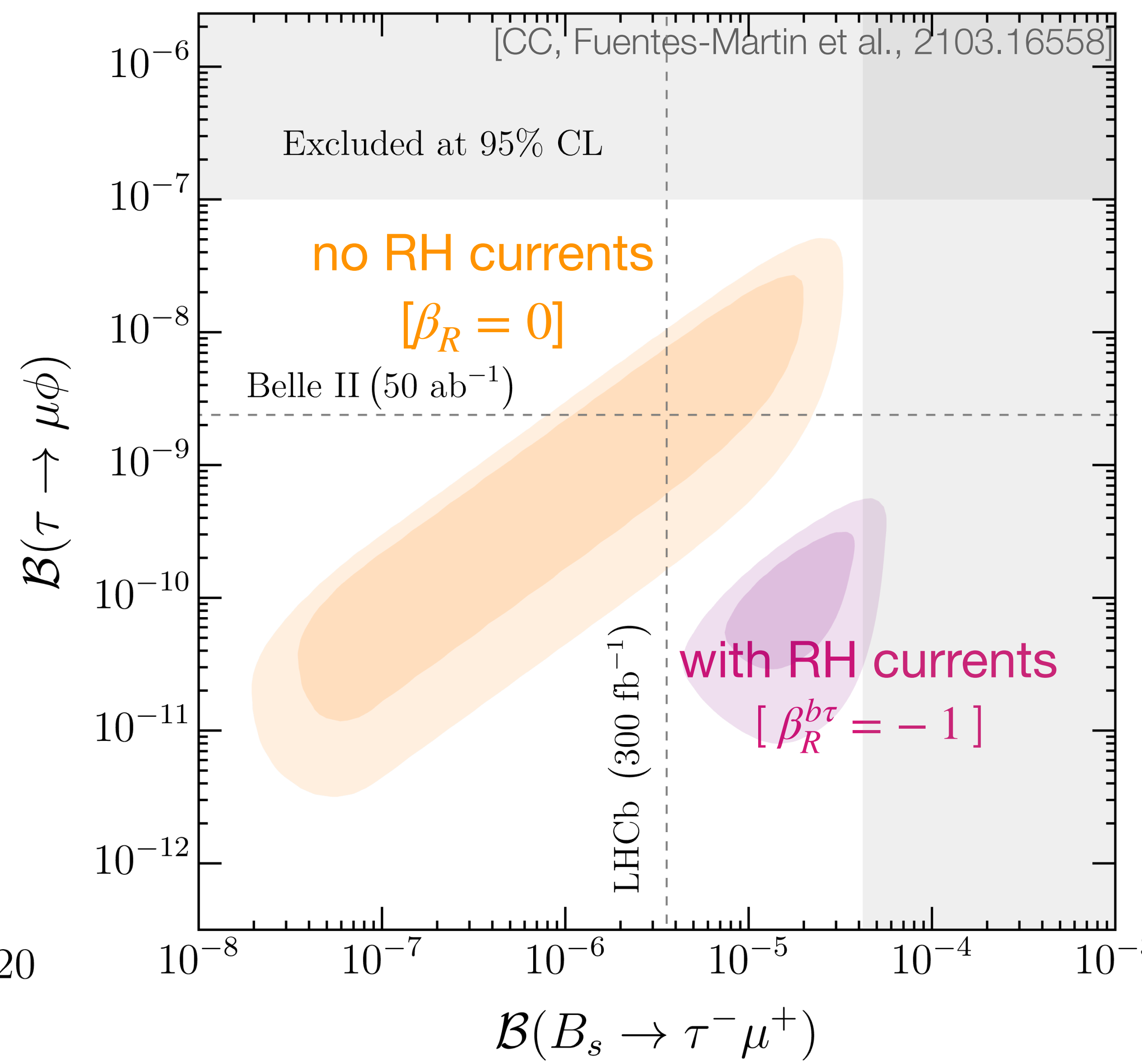
✓ Good description of all low-energy data with U(2)-like flavor structure.

Low-energy predictions for the U_1

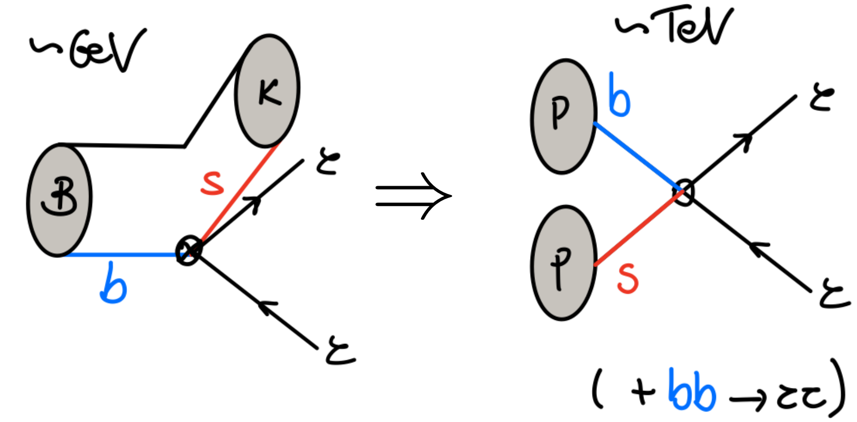
- large $b \to s\tau\tau$



- large τ/μ LFV in $b \to s\tau\mu$ and τ decays

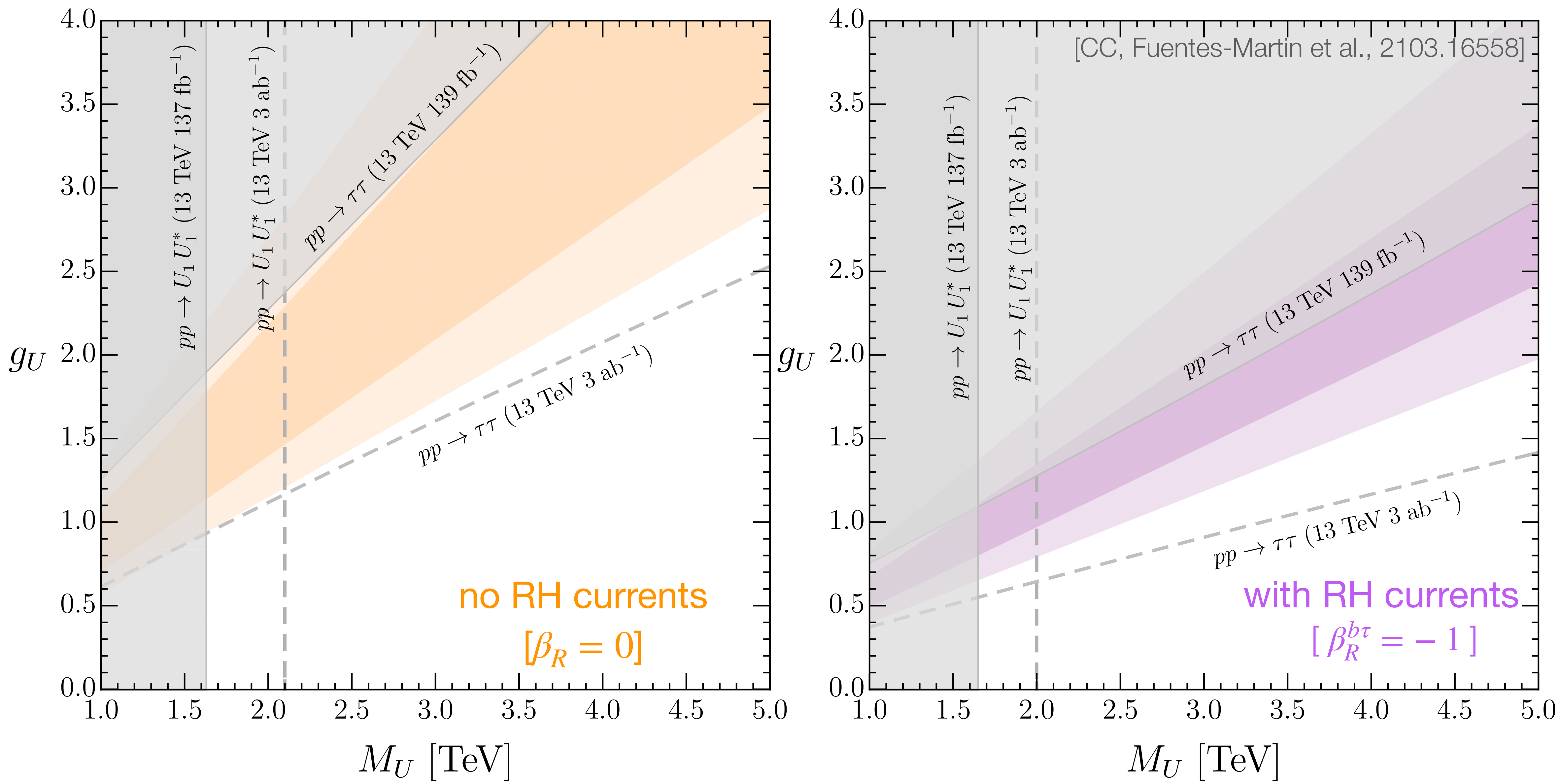


High-pT bounds for the U_1

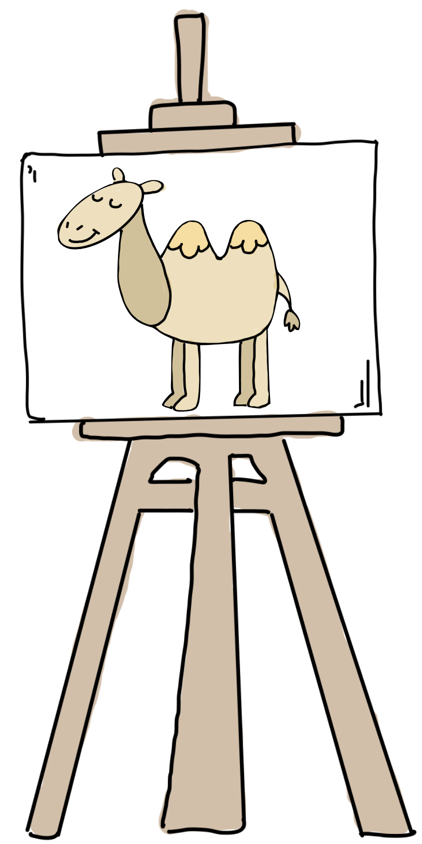


The same interaction can be probed in **di-tau tails**.

Expected excess in $pp \to \tau^+\tau^-$! [Faroughy et al, 1609.07138]



NP interpretation (III): UV completing the U_1



UV-completing the U_1: the gauge path

[Pati, Salam, Phys. Rev. D10 (1974) 275]

$$\boldsymbol{U_1 \sim (3,1,2/3) \dashrightarrow SU(4) \dashrightarrow \mathrm{PS} = SU(4) \times SU(2)_L \times SU(2)_R}$$

$$SU(4) \sim \begin{pmatrix} G^a & U^\alpha \\ (U^\alpha)^* & Z' \end{pmatrix} \qquad \psi_{L,R} = \begin{bmatrix} q^\alpha_{L,R} \\ q^\beta_{L,R} \\ q^\gamma_{L,R} \\ l^\delta_{L,R} \end{bmatrix}$$

$\mathrm{PS/SM} \ni U_1, Z'$

(strongly coupled
& flavor universal*)

- ✘ flavor-blind U_1 mediates $K_L \to \mu e \;\; \Rightarrow \;\; m_{U_1} \gtrsim 100\,\mathrm{TeV}$
- ✘ *extra fermions can make the U_1 non-universal, not the Z'
- ✘ strongly coupled, universal Z' would be excessively produced at the LHC

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[Pati, Salam, Phys. Rev. D10 (1974) 275]

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- ✘ strongly coupled, universal Z' would be excessively produced at the LHC

$$\mathcal{G}_{4321} = SU(4) \times SU(3)' \times SU(2)_L \times U(1)' \qquad 4321/\mathrm{SM} \ni U_1, Z', G' \sim (8,1,0)$$

- ✓ $SU(4)$ decorrelated from $SU(3)_c$. High-pT problem solved for $g_4 \gg g_1, g_3$
- ✓ both Z' and U_1 can be flavor non-universal

[Georgi and Y. Nakai, 1606.05865;
Diaz, Schmaltz, Zhong, 1706.05033;
Di Luzio, Greljo, Nardecchia, 1708.08450]

Non-universality via mixing

[di Luzio, Greljo, Nardecchia, 1708.08450;
di Luzio, Fuentes-Martin, Greljo, Nardecchia, Renner 1808.00942]

$$\mathcal{G}_{4321} = SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$$

$$\Psi = \begin{pmatrix} Q \\ L \end{pmatrix}$$

$i = 1,2,3$

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
$q_L'^i$	1	3	2	$1/6$
$u_R'^i$	1	3	1	$2/3$
$d_R'^i$	1	3	1	$-1/3$
$\ell_L'^i$	1	1	2	$-1/2$
$e_R'^i$	1	1	1	-1
Ψ_L^i	4	1	2	0
Ψ_R^i	4	1	2	0
H	1	1	2	$1/2$
Ω_3	$\bar{4}$	3	1	$1/6$
Ω_1	$\bar{4}$	1	1	$-1/2$

SM fields all families

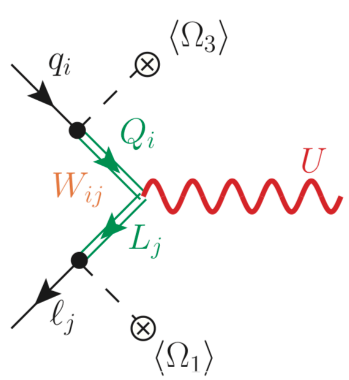
vectorlike fermions

scalar sector

▸ **flavor-universal gauge interactions**

- all SM families have SM-like charges under 321
- only vector-like fermions are charged under 4

• no direct NP couplings to SM fields.



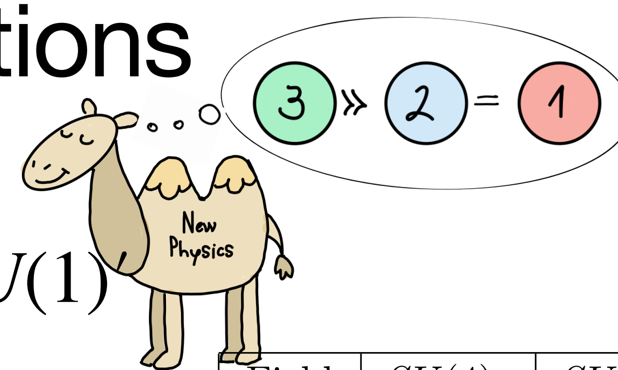
• flavor structure of U_1 interactions for B anomalies generated via hierarchical choice of mixing angles

→ 3rd family has to be the "*most composite*"

• can have U_1 coupled only to left-handed SM fields

• Yukawa couplings as in the SM. No connection flavor anomalies & hierarchies.

Non-universal gauge interactions



[Bordone, CC, Fuentes-Martin, Isidori 1712.01368, 1805.09328; Greljo, Stefanek, 1802.04274; CC, Fuentes-Martin, Isidori 1903.11517]

$$\mathcal{G}_{4321} = SU(4)_3 \times SU(3)'_{1+2} \times SU(2)_L \times U(1)'$$

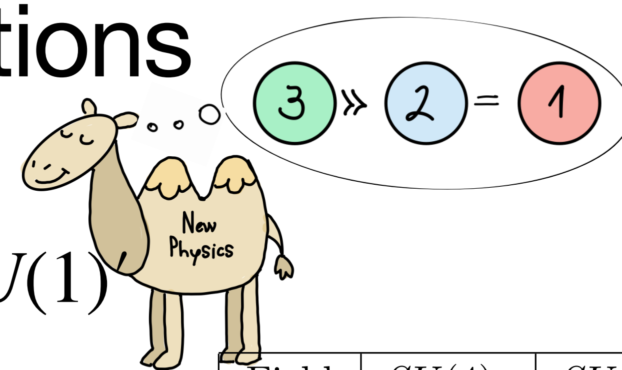
- **flavor non-universal gauge interactions**

- light SM families: SM-like charges under 321
- vectorlike fermions and 3rd SM family charged under 4
  - accidental $U(2)^5$ $\quad \psi = (\psi_1\ \psi_2\ \ \psi_3)$
  - direct NP coupling to 3rd SM family (L+R)
  - TeV scale 3rd family quark-lepton unification

$i = 1{,}2$

	Field	$SU(4)_3$	$SU(3)_{1+2}$	$SU(2)_L$	$U(1)_{Y'}$
SM fields: 1st & 2nd family	q_L^i	**1**	**3**	**2**	$1/6$
	u_R^i	**1**	**3**	**1**	$2/3$
	d_R^i	**1**	**3**	**1**	$-1/3$
	ℓ_L^i	**1**	**1**	**2**	$-1/2$
	e_R^i	**1**	**1**	**1**	-1
3rd family	ψ_L^3	**4**	**1**	**2**	0
	$\psi_{R_{u,d}}^3$	**4**	**1**	**1**	$\pm 1/2$
vectorlike fermions	χ_L^i	**4**	**1**	**2**	0
	χ_R^i	**4**	**1**	**2**	0
scalar sector	H	**1**	**1**	**2**	$1/2$
	Ω_1	$\bar{\mathbf{4}}$	**1**	**1**	$-1/2$
	Ω_3	$\bar{\mathbf{4}}$	**3**	**1**	$1/6$
	Ω_{15}	**15**	**1**	**1**	0

Non-universal gauge interactions



[Bordone, CC, Fuentes-Martin, Isidori 1712.01368, 1805.09328; Greljo, Stefanek, 1802.04274; CC, Fuentes-Martin, Isidori 1903.11517]

$$\mathcal{G}_{4321} = SU(4)_3 \times SU(3)'_{1+2} \times SU(2)_L \times U(1)'$$

$i = 1,2$

Field	$SU(4)_3$	$SU(3)_{1+2}$	$SU(2)_L$	$U(1)_{Y'}$	
					SM fields
q_L^i	**1**	**3**	**2**	$1/6$	1st & 2nd family
u_R^i	**1**	**3**	**1**	$2/3$	
d_R^i	**1**	**3**	**1**	$-1/3$	
ℓ_L^i	**1**	**1**	**2**	$-1/2$	
e_R^i	**1**	**1**	**1**	-1	
ψ_L^3	**4**	**1**	**2**	0	3rd family
$\psi^3_{R_{u,d}}$	**4**	**1**	**1**	$\pm 1/2$	
χ_L^i	**4**	**1**	**2**	0	vectorlike fermions
χ_R^i	**4**	**1**	**2**	0	
H	**1**	**1**	**2**	$1/2$	scalar sector
Ω_1	$\bar{\mathbf{4}}$	**1**	**1**	$-1/2$	
Ω_3	$\bar{\mathbf{4}}$	**3**	**1**	$1/6$	
Ω_{15}	**15**	**1**	**1**	0	

- **flavor non-universal gauge interactions**

- light SM families: SM-like charges under 321
- vectorlike fermions and 3rd SM family charged under 4

    - accidental $U(2)^5$ $\quad \psi = ((\psi_1\ \psi_2)\ \psi_3)$
    - direct NP coupling to 3rd SM family (L+R)
    - TeV scale 3rd family quark-lepton unification

- **$U(2)^5$ broken by SM-vectorlike mixing**

Leading breaking:

- U_1 couplings to light families for B anomalies
- 2-3 CKM mixing

✓ connection flavor anomalies & hierarchies!

Subleading breaking:

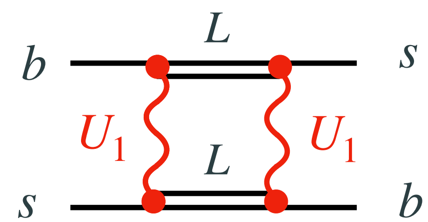
constrained by $K_L \to \mu e$, K-$\bar{K}$ and D-$\bar{D}$

*Mild 2-3 down alignment required to suppress G' and Z' contribution to B_s-$\bar{B}_s$

UV-sensitive low-energy observables

[Selimovic et al., 2009.11296]
[CC, Fuentes et al., 2103.16558]

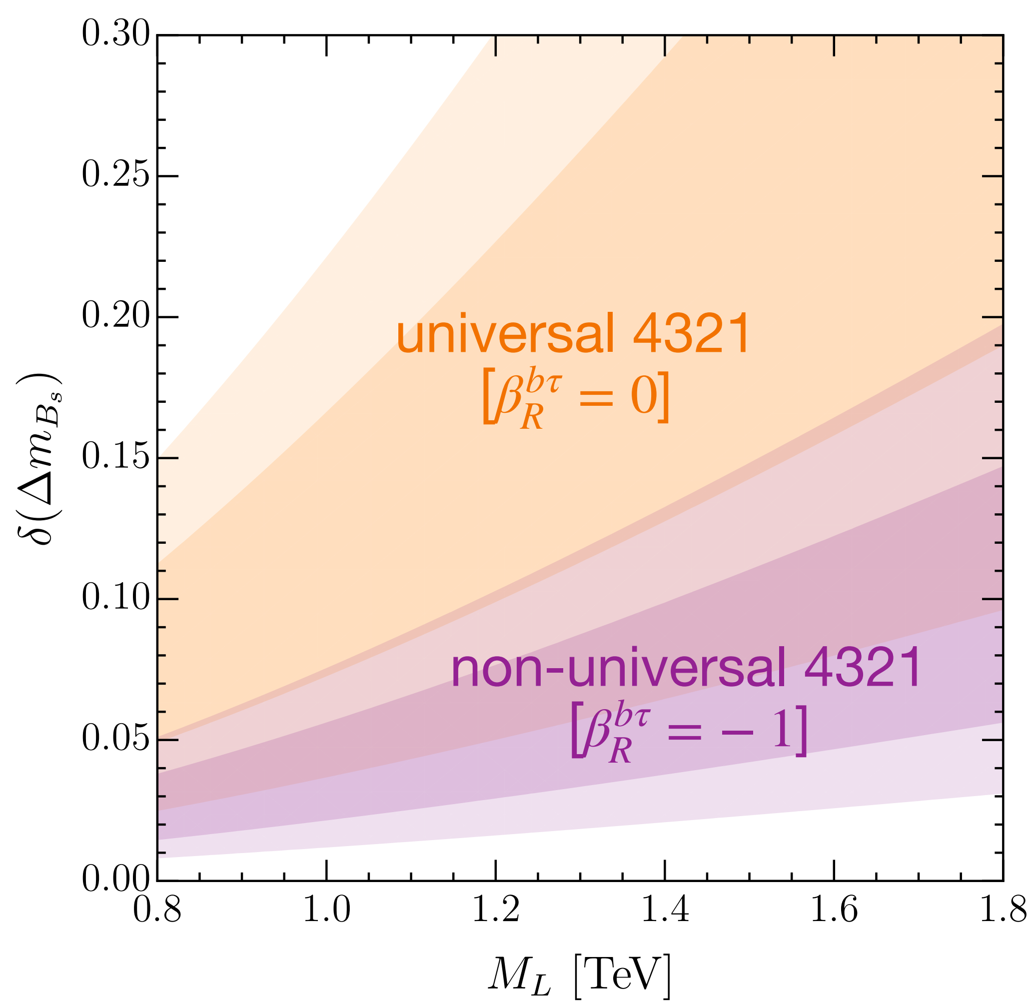
- B_s-$\bar{B}_s$ mixing



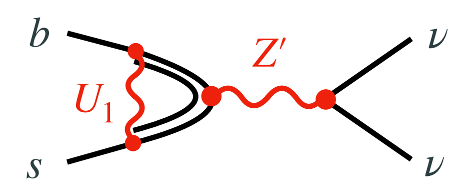
$$\frac{C_{bs}^{\mathrm{NP-tree}}}{C_{bs}^{\mathrm{SM}}} \propto \left(\beta_L^{s\tau *}\right)^2 M_L^2$$

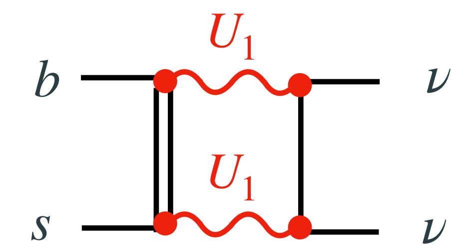
$U(2)_q$ breaking (for $R_{D^{(*)}}$)

→ vector-like leptons must be light, in the reach of the LHC

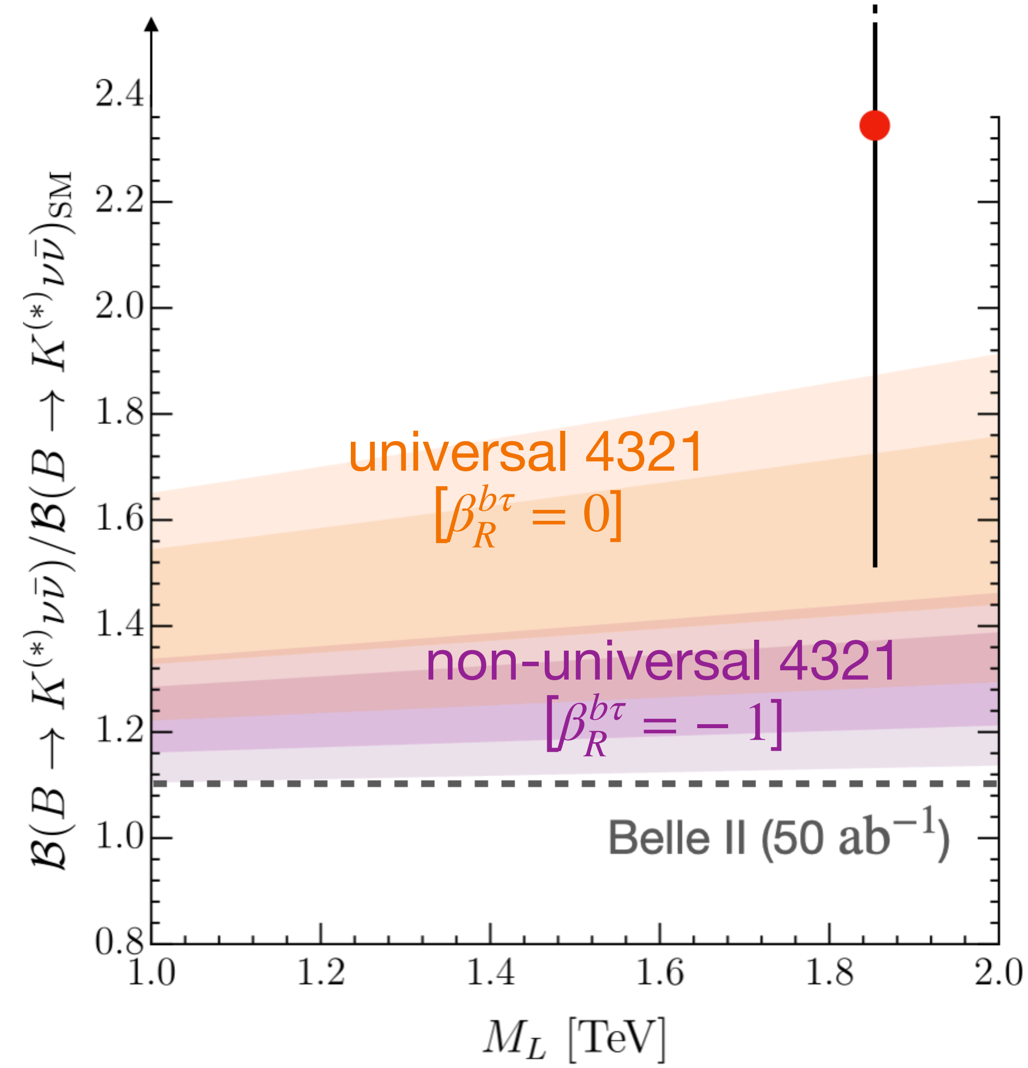


- $B \to K\nu\bar{\nu}$

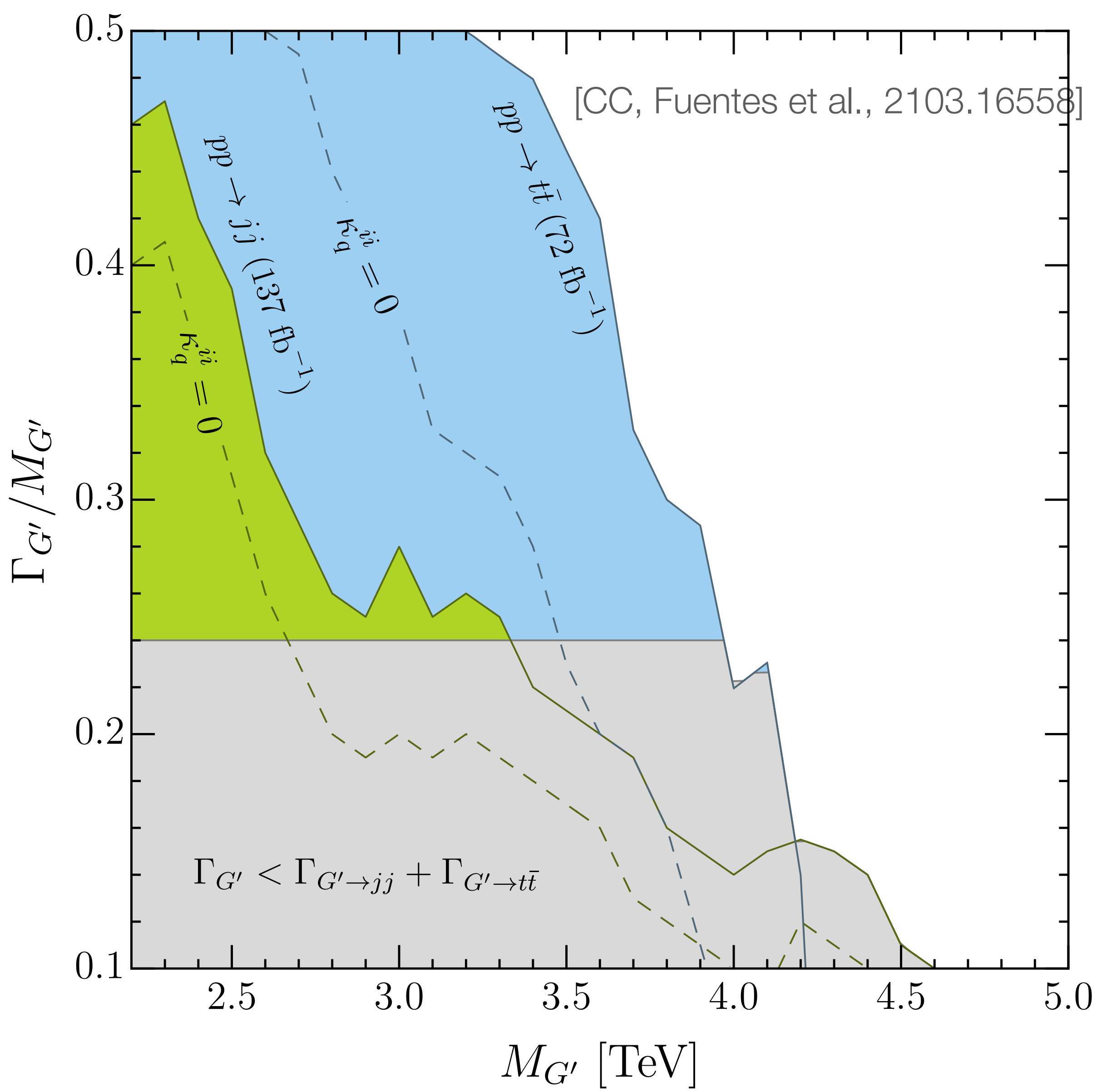




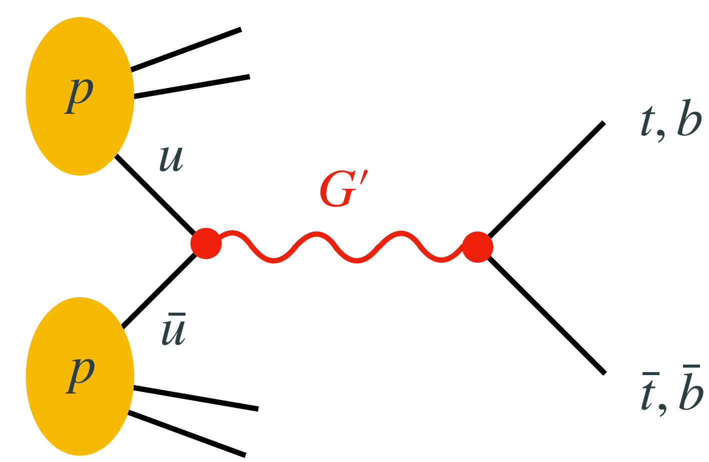
→ 20-50% enhancement over the SM (also driven by $R_{D^{(*)}}$), in the reach of Belle II



Coloron direct searches at the LHC



Relevant collider signatures for G'
("coloron" = heavy color-octet vector)



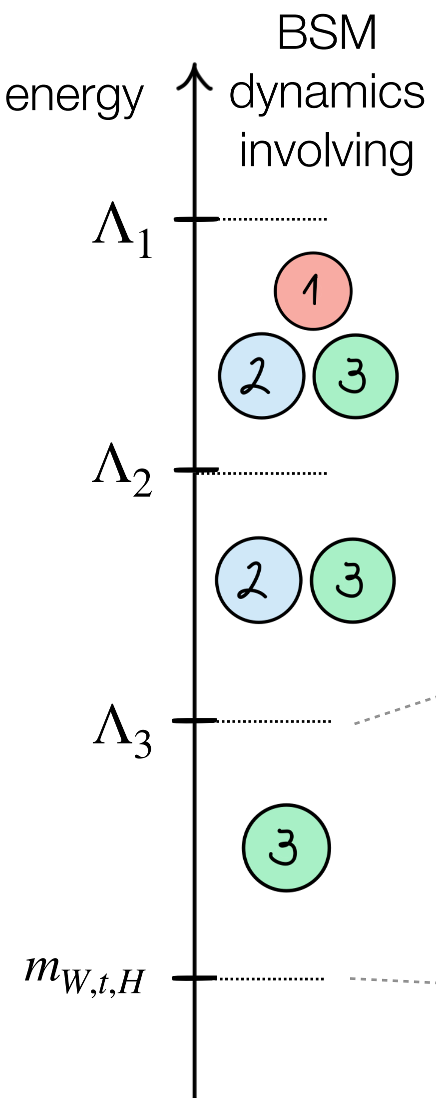
→ G'-mediated $pp \to tt$ gives the strongest constraint on the overall scale of the model!

$$M_{G'} \sim \sqrt{2}\, M_{\mathrm{LQ}}$$

A three-scale picture

[Barbieri, 2103.15635,
Bordone, CC, Fuentes, Isidori 1712.01368
Panico, Pomarol, 1603.06609 Dvali, Shiftman, '00, …]

B anomalies might hint at a three-scale picture:

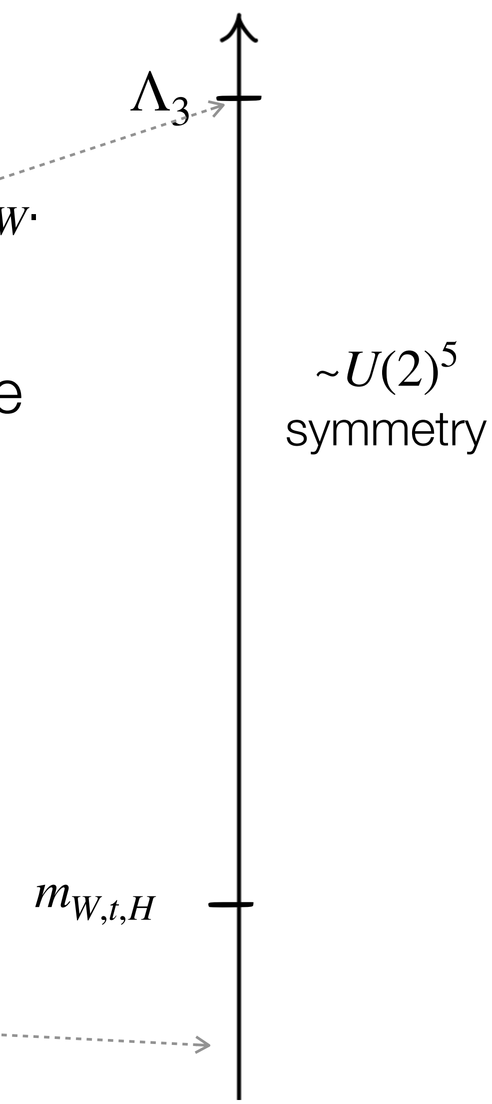


New, non-universal interactions (for us: gauge) acting on the i-th SM family switch on at $\Lambda_1 \gg \Lambda_2 \gg \Lambda_3 \gg m_W$.

Yukawa couplings are different because they originate at these different scales.

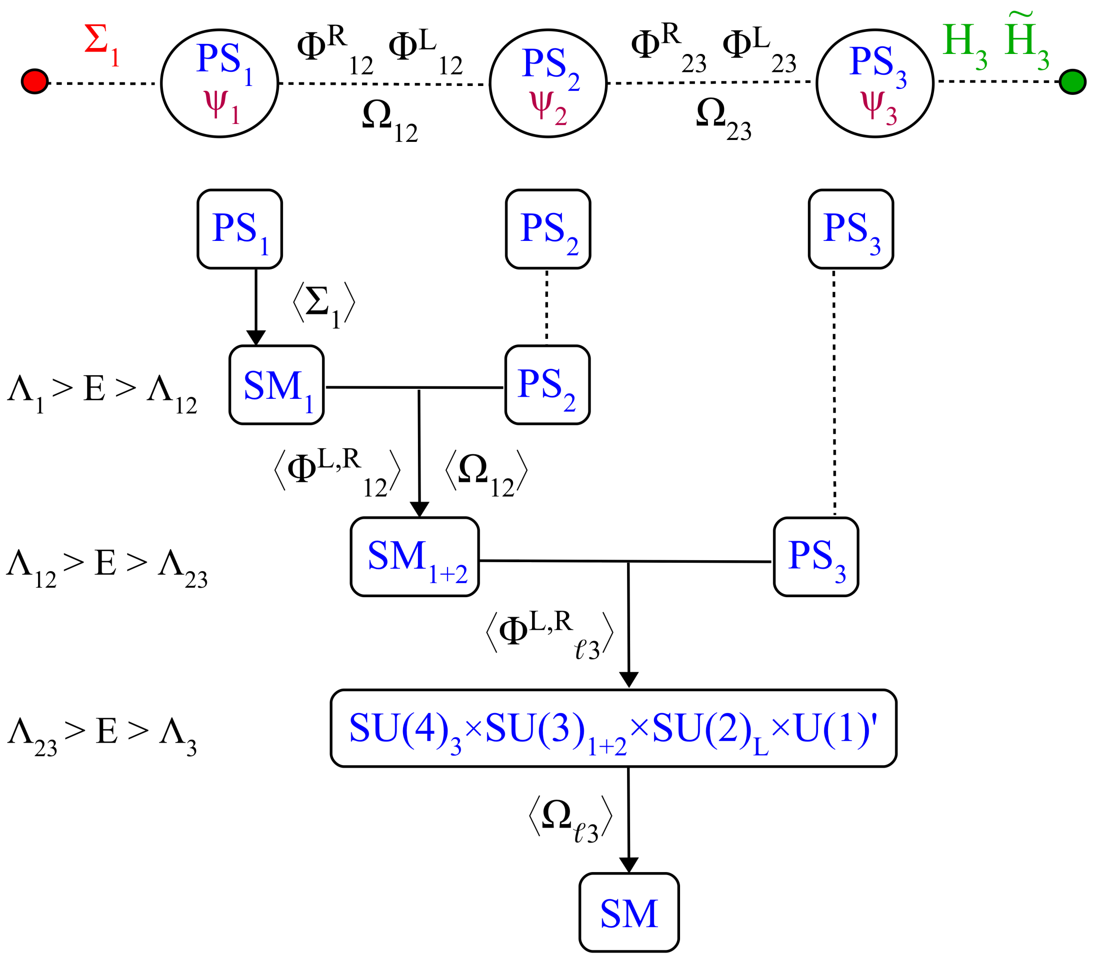
New Physics is flavor non-universal; universality is a low-energy accident.

Λ_3 can be as low as few TeV.



Non-universal Pati-Salam unification

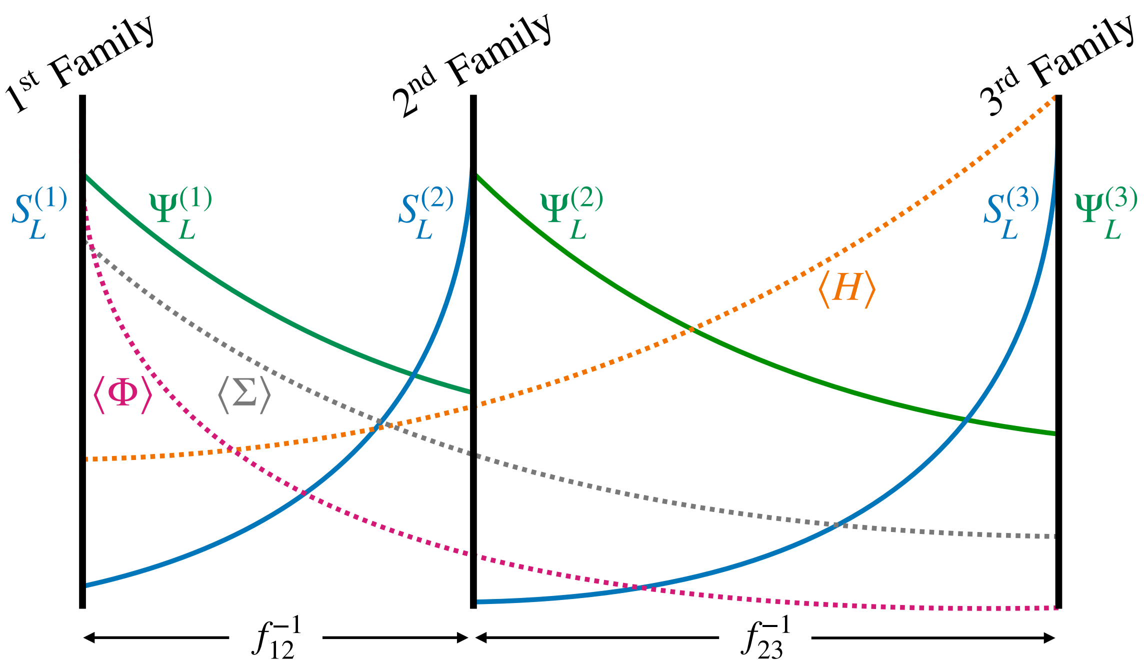
- **PS³: 4D three-site model**



[Bordone, CC, Fuentes, Isidori 1712.01368]

- **5D construction**

warped compact extra dimension with multiple 4-dimensional branes



[Fuentes-Martin, Isidori, Pagès, Stefanek, 2012.10492]
[Fuentes-Martin, Isidori, Lizana, Stefanek, Selimovic, in progress]

NP interpretation (IV): g-2 in 4321 models

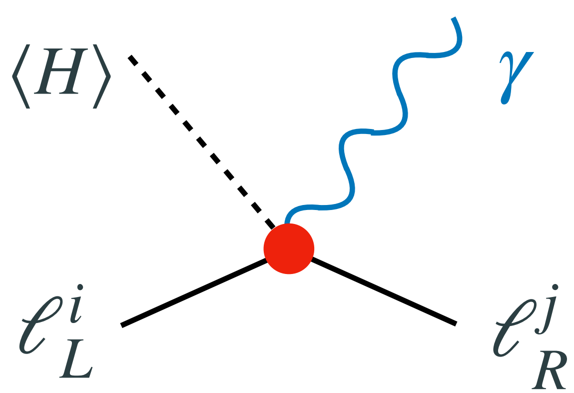
[inspired by Ben Stefanek's Virtual Seminar @ Peking and
Beijing Flavor Anomaly Seminar Series on June 17, 2021]

$(g-2)_\mu$ as New Physics

The discrepancy is roughly the same size as the SM electroweak contribution:

$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} \approx (a_\mu^{\text{SM}})_{\text{EW}} \approx \frac{m_\mu^2}{16\pi^2} \times \frac{4\,G_F}{\sqrt{2}} \approx 3 \times 10^{-9}$$

→ **New physics scale?**



$$\Delta a_\mu^{\text{NP}} \approx \frac{g_{\text{NP}}^2}{16\pi^2}\frac{m_\mu^2}{M_{\text{NP}}^2} \implies M_{\text{NP}} \sim v_{\text{EW}}$$

$$\Delta a_\mu^{\text{NP}} \approx \frac{g_{\text{NP}}^2}{16\pi^2}\frac{m_\mu m_f}{M_{\text{NP}}^2}$$

Chiral Enhancement

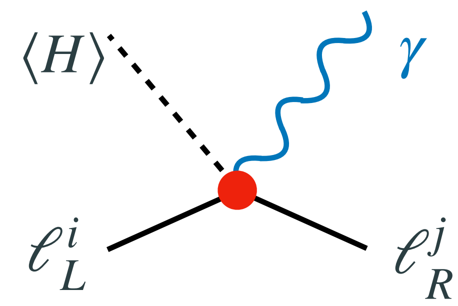
$$\implies M_{\text{NP}} \sim \sqrt{N_c}\begin{cases} 1\ \text{TeV} & m_f = m_b \\ 6\ \text{TeV} & m_f = m_t \end{cases}$$

$(\text{Max} \sim 10\ \text{TeV})$

*Another option is light NP $M_{\text{NP}} < v_{\text{EW}}$ with small couplings.

$(g-2)_\mu$ as New Physics

$$\mathcal{L}_{\rm EFT} \supset \frac{e}{16\pi^2}\frac{v}{\sqrt{2}} C_{\ell\ell'}\left(\bar{\ell}_L \sigma_{\mu\nu} \ell'_R F^{\mu\nu}\right)$$



$\ell = \ell'$: Magnetic & electric moments

$(g-2)_\mu \longrightarrow \mathrm{Re}(C_{\mu\mu}) \approx (4-7)\times 10^{-3}\ \mathrm{TeV}^{-2}$

$\mathrm{eEDM} \longrightarrow \mathrm{Im}(C_{ee}) \lesssim 10^{-10}\ \mathrm{TeV}^{-2}$

$\ell \neq \ell'$: cLFV, in particular $\ell \to \ell'\gamma$

$\mu \to e\gamma \longrightarrow |C_{\mu e}| \lesssim 10^{-7}\ \mathrm{TeV}^{-2}$

$\tau \to \mu\gamma \longrightarrow |C_{\tau\mu}| \lesssim 2\times 10^{-3}\ \mathrm{TeV}^{-2}$

[Calibbi, Lopez-Ibanez, Melis, Vives, 2104.03296]

$\Longrightarrow$ cLFV bounds require strong alignement $\quad C_{\mu e}/C_{\mu\mu} \lesssim 10^{-5}\,,\ C_{\tau\mu}/C_{\mu\mu} \lesssim 0.5$

much stronger than what naively expected from Yukawa-like flavor structure:

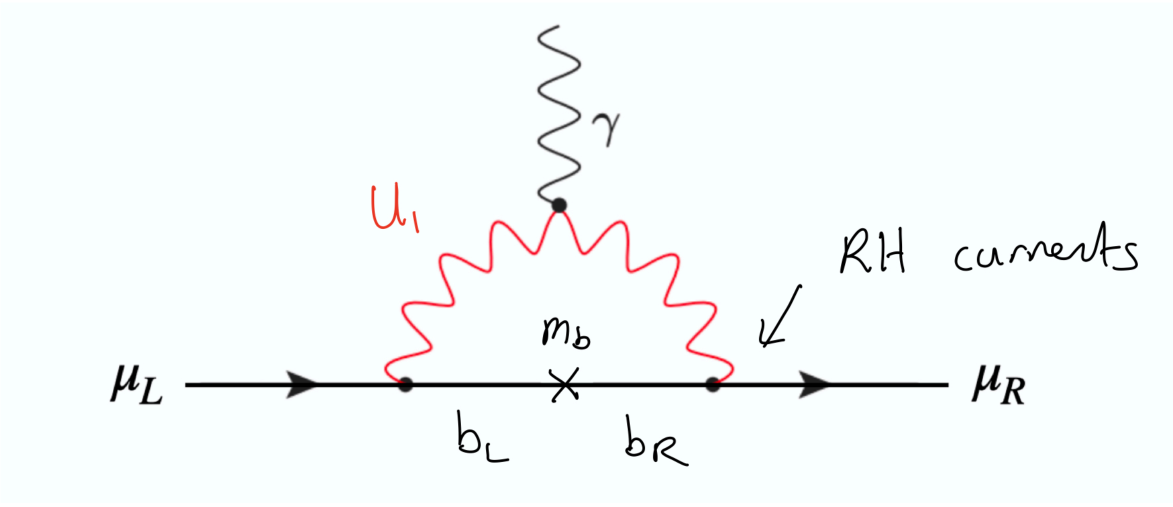
$$C_{\mu e}/C_{\mu\mu} \sim \sqrt{m_e/m_\mu} \approx 0.07\,,\ C_{\tau\mu}/C_{\mu\mu} \sim \sqrt{m_\tau/m_\mu} \approx 4$$

$\Longrightarrow$ Not easy to reconcile $(g-2)_\mu$ with both B anomalies.

U_1 for both anomalies and g-2?

We already know the U_1 leptoquark works for B-anomalies. What about for (g-2)?

Need large U_1 coupling to μ_R, b_R:



$$\Delta a_\mu \sim \frac{N_c}{4\pi^2}\frac{m_\mu m_b}{M_{\mathrm{LQ}}^2}\frac{g_4^2}{2} s_{\mu_L} s_{\mu_R}$$

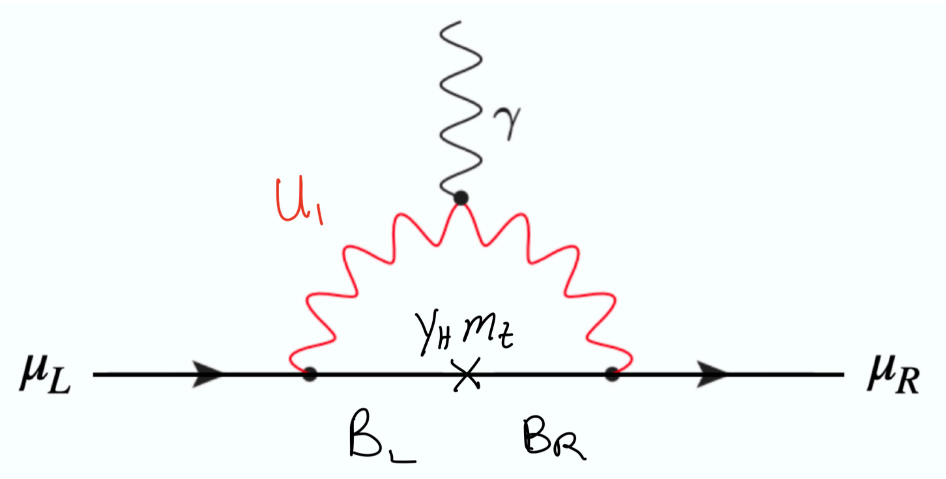
$$\sim 10^{-9}\left(\frac{3\ \mathrm{TeV}}{m_{\mathrm{LQ}}}\right)^2\left(\frac{s_{\mu_L}}{0.2}\right)\left(\frac{s_{\mu_R}}{0.2}\right)$$

But RH currents generate the scalar operator $\mathcal{O}_s \sim \dfrac{m_b}{m_\mu} V_{ts}\left(\bar{s}_L b_R\right)\left(\bar{\mu}_R \mu_L\right)$

….would give too large a contribution to $B_s \to \mu^+\mu^-$!

U_1 for both anomalies and g-2?

Try with vector-like fermions in the loop:



$$\chi_{L,R} \sim (4,1,2,0)\,, \qquad \chi \supset \begin{pmatrix} Q \\ L \end{pmatrix} \quad \xi \supset \begin{pmatrix} D \\ E \end{pmatrix}$$

$$\xi_{L,R} \sim (4,1,1,-1/2)$$

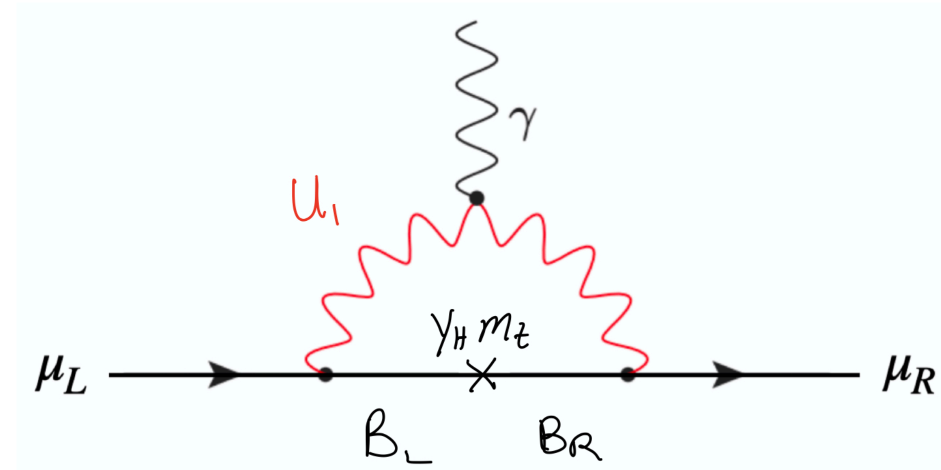
VL mass contribution from Higgs: $\mathscr{L} \supset -\bar{\chi}_L y_H H \xi_R - \bar{\chi}_R \tilde{y}_H H \xi_L$

$$\Delta a_\mu \sim \frac{N_c}{4\pi^2}\frac{m_\mu m_t}{M_{\rm LQ}^2}\frac{g_4^2}{2} y_H s_{\mu_L} s_{\mu_R} \qquad \sim 3\times 10^{-9}\left(\frac{4\ \text{TeV}}{m_{\rm LQ}}\right)^2\left(\frac{s_{\mu_L}}{0.2}\right)\left(\frac{s_{\mu_R}}{0.05}\right)\left(\frac{y_H}{1}\right)$$

✔ for $y_H, \tilde{y}_H \sim 1$, get full chiral enhancement!

U_1 for both anomalies and g-2?

Try with vector-like fermions in the loop:



$$\chi_{L,R} \sim (4,1,2,0)\,, \qquad \chi \supset \begin{pmatrix} Q \\ L \end{pmatrix} \quad \xi \supset \begin{pmatrix} D \\ E \end{pmatrix}$$

$$\xi_{L,R} \sim (4,1,1,-1/2)$$

VL mass contribution from Higgs: $\mathscr{L} \supset -\bar{\chi}_L y_H H \xi_R - \bar{\chi}_R \tilde{y}_H H \xi_L$

$$\Delta a_\mu \sim \frac{N_c}{4\pi^2} \frac{m_\mu m_t}{M_{\rm LQ}^2} \frac{g_4^2}{2} y_H s_{\mu_L} s_{\mu_R} \quad \sim 3 \times 10^{-9} \left(\frac{4\ \text{TeV}}{m_{\rm LQ}}\right)^2 \left(\frac{s_{\mu_L}}{0.2}\right) \left(\frac{s_{\mu_R}}{0.05}\right) \left(\frac{y_H}{1}\right)$$

✔ for $y_H, \tilde{y}_H \sim 1$, get full chiral enhancement!

✘ SM chiral - VL mixing gives large tree-level correction to down-type Yukawas

$$y_\mu = y_\mu^H + \delta y_\mu^{\rm mix} + \delta y_\mu^{\rm loop} \sim 6 \times 10^{-4} \qquad \delta y_\mu^{\rm mix} \sim y_H s_{\mu_L} s_{\mu_R} \sim 10^{-2}$$

✘ no control for cLFV. Main problem is the expectation for $\tau \to \mu\gamma$: $\dfrac{C_{\tau\mu}}{C_{\mu\mu}} \sim \dfrac{1}{s_{\mu_L}} \sim 5 \gg 0.5$

$\Longrightarrow$ **U_1 vector LQ as a single mediator fails.**

A possible solution within universal 4321

Enlarge the scalar sector and add a softly broken Z_2 symmetry can work!

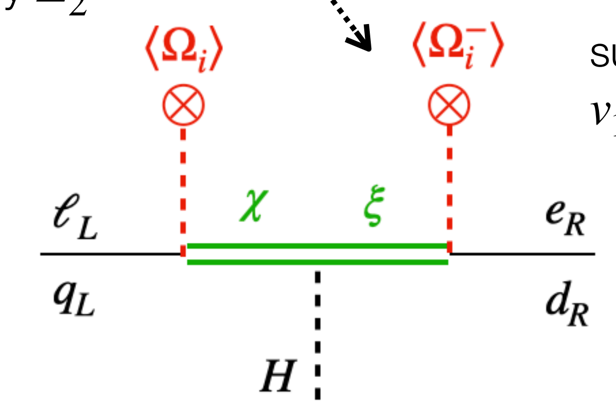
Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$	Z_2	Flavor
q_L^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$+$	$\mathbf{3}_q$
u_R^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	$+$	$\mathbf{3}_u$
d_R^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$-$	$\mathbf{3}_d$
ℓ_L^i	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$+$	$\mathbf{3}_\ell$
e_R^i	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$	$-$	$\mathbf{3}_\ell$
$\chi_{L,R}^i$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0	$+$	$\mathbf{3}_\ell$
$\xi_{L,R}^i$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$	$+$	$\mathbf{3}_\ell$
H	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$+$	$\mathbf{1}$
$\Omega_1^\pm$	$\bar{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$	$\pm$	$\mathbf{1}$
$\Omega_3^\pm$	$\bar{\mathbf{4}}$	$\mathbf{3}$	$\mathbf{1}$	$1/6$	$\pm$	$\mathbf{1}$
Ω_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$	0	$+$	$\mathbf{1}$

[Fuentes-Martin, Greljo, Stefanek, Thomsen, in progress]

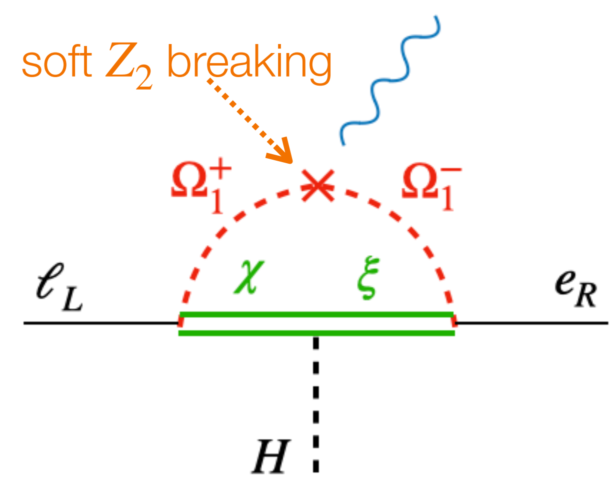
$$y_\mu = \cancel{y_\mu^H} + \boxed{\delta y_\mu^{\rm mix}} + \delta y_\mu^{\rm loop}$$

forbidden by Z_2

suppressed if $v_{1+}/v_{1-} \equiv \tan\beta_1 \gg 1$



$(g-2)_\ell$



large $\tan\beta_1$

$$\Delta a_\mu \approx \frac{m_\mu^2}{16\pi^2}\frac{4\pi^2}{M_\Omega^2} \approx \frac{m_\mu m_b}{16\pi^2 M_\Omega^2} \approx 3\times 10^{-9}\left(\frac{1\ \mathrm{TeV}}{M_\Omega}\right)^2$$

Conclusions and outlook

B anomalies could be the manifestation of a new interaction violating LFU.
In the coming years, on-going experiments will have the final word about their nature!

- Taken together, they point to TeV-scale leptoquark(s) coupled dominantly to the 3rd family.
  → flavor non-universal gauge interactions?
  → multi-scale picture at the origin of flavor?
  Explaining also the (g-2) is possible, but requires additional ingredients.

- Consistent picture, but present data in $b \to c\tau\nu$ require NP to be quite close: if $R_{D^{(*)}}$ stays, we NP effects must show up soon, at low and high energy.
  Need experimental corroboration to guide us.