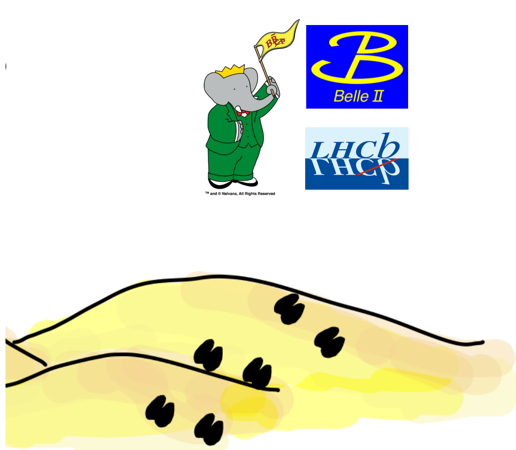
B-physics Anomalies: from Data to New Physics Models

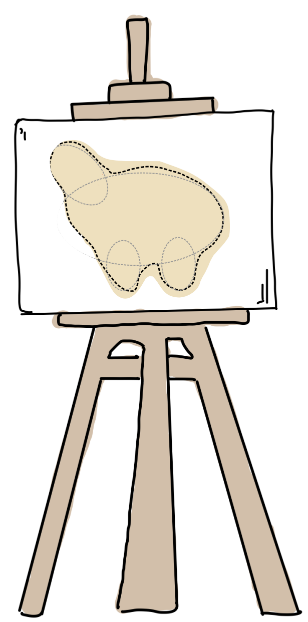
Claudia Cornella
Johannes Gutenberg University Mainz

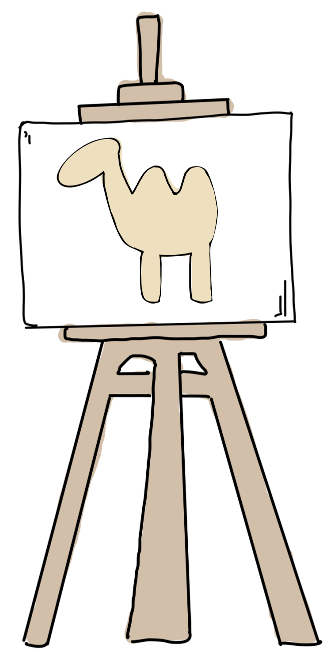
From Data to New Physics models

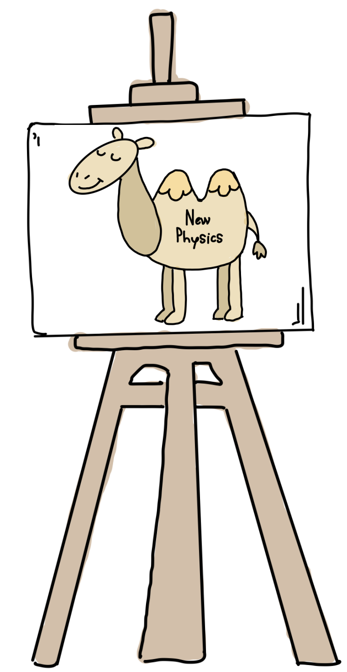
DATA → EFT → SIMPLIFIED MODEL → UV COMPLETION

[Vitalii] [Luca] [David, Nudzeim, Ben, Joe]



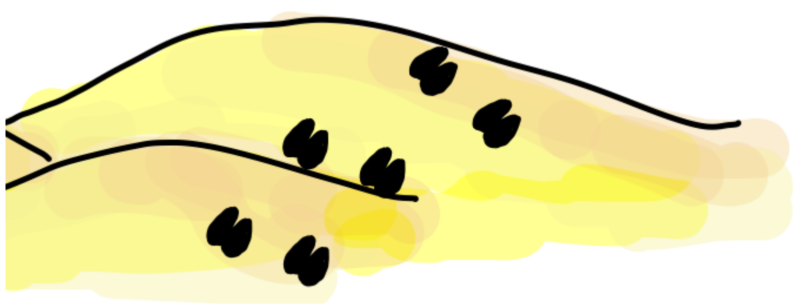






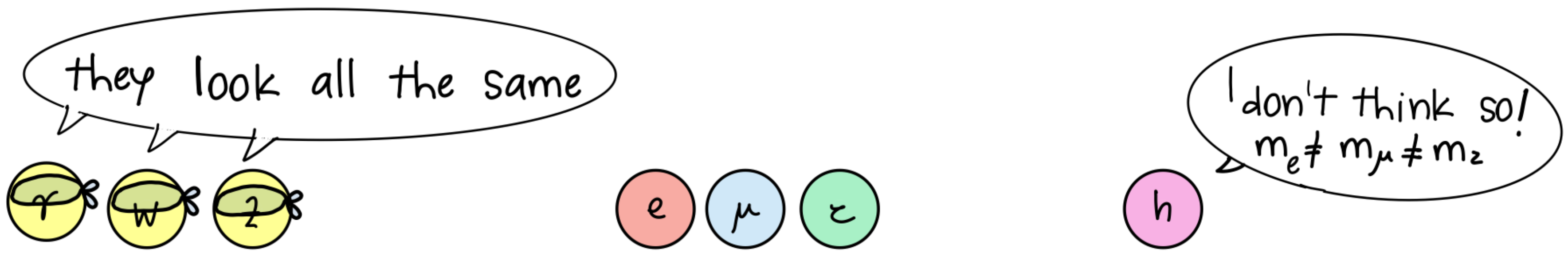
Here: $b \to s \ell^+ \ell^-$ & $b \to c \ell \nu$

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)

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 $b \to cl\nu$

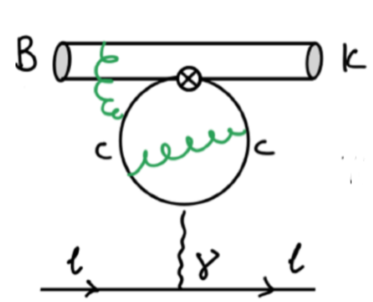
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})} > R_{D^{(*)}}^{\rm SM}$$

$\sim 3\,\sigma$

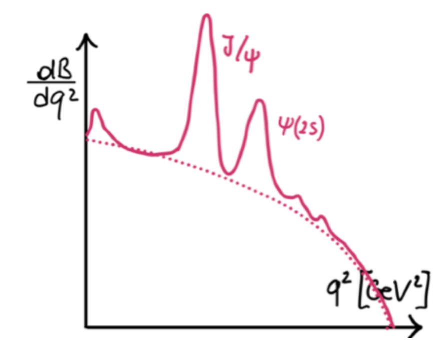
The $b \to sll$ anomalies [Vitalii & Luca's talks]

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

"not-so-clean"



⇒



- 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]

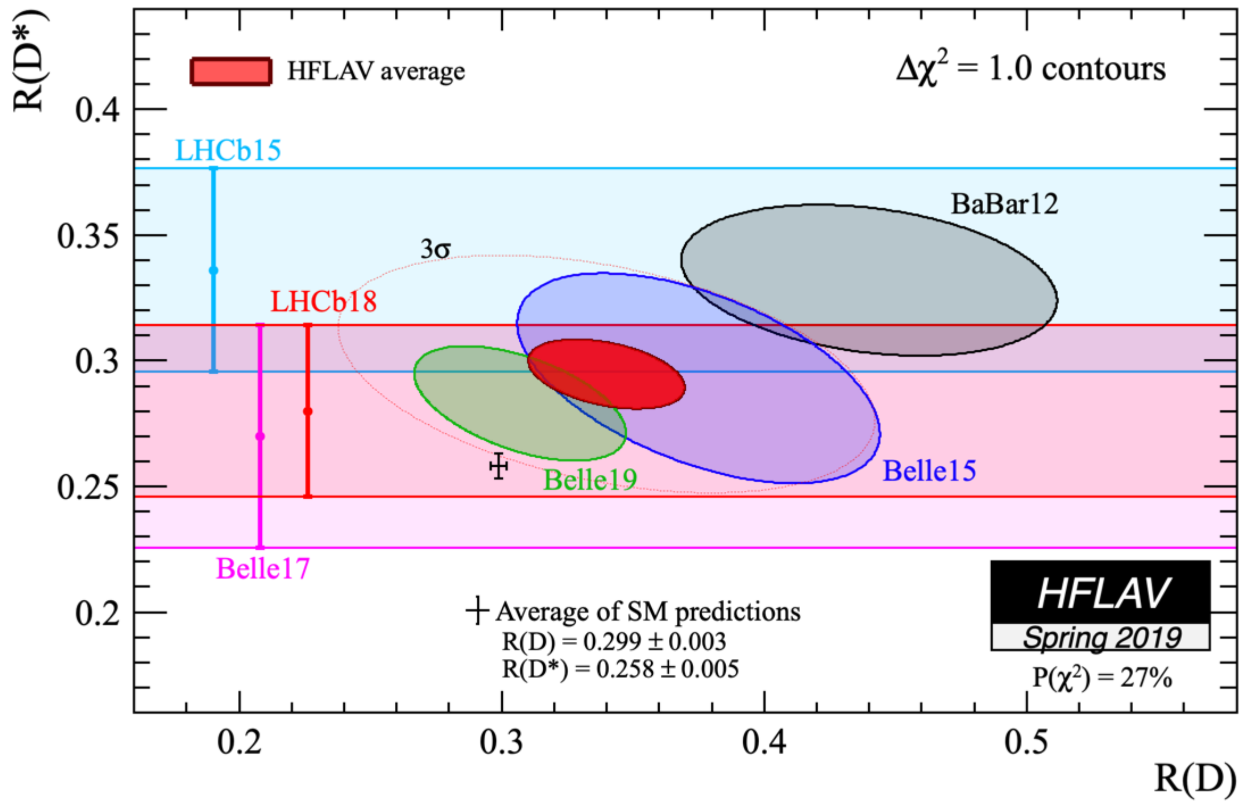
LHCb results on LFU ratios this year:

$R_K^{[1.1,6]}$ update ($3.1\,\sigma$) [LHCb, 2103.11769]

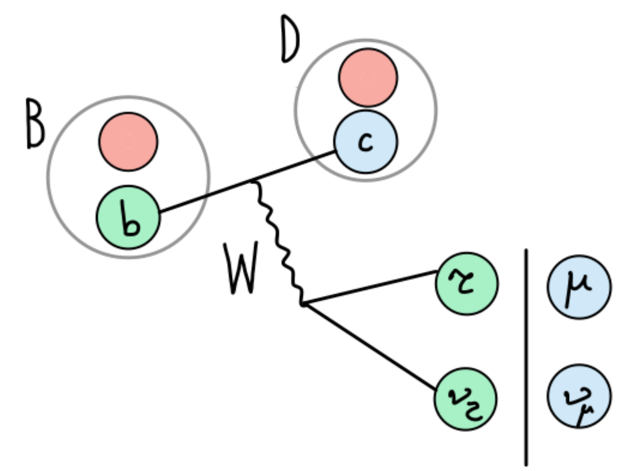
first results for R_{K_s} and $R_{K^{*+}}$ [LHCb, 2110.09501]

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



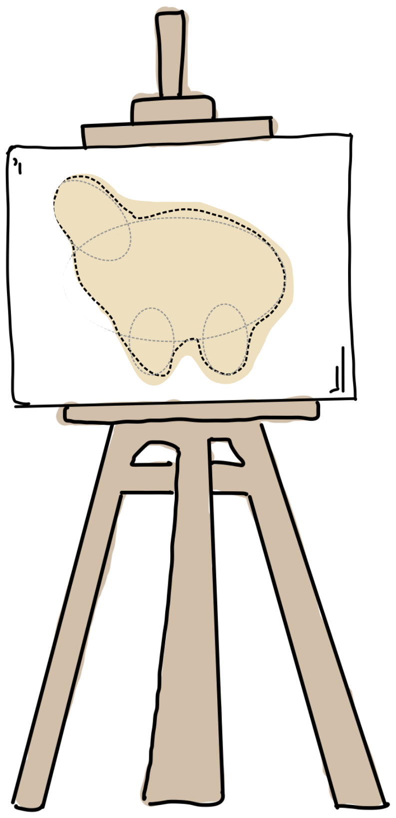
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}$$



- $\sim 15\,\%$ 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 $b \to sll$

[see Luca's talk]

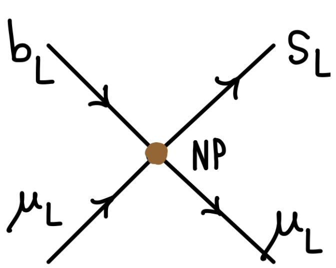
$$\mathscr{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{\alpha}{4\pi} \sum_i C_i O_i$$

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

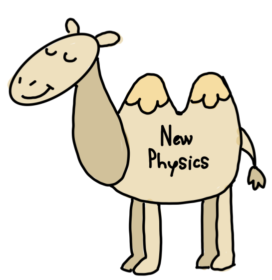
$$O_{10}^\mu = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\, \gamma^\mu \gamma_5\, \mu)$$

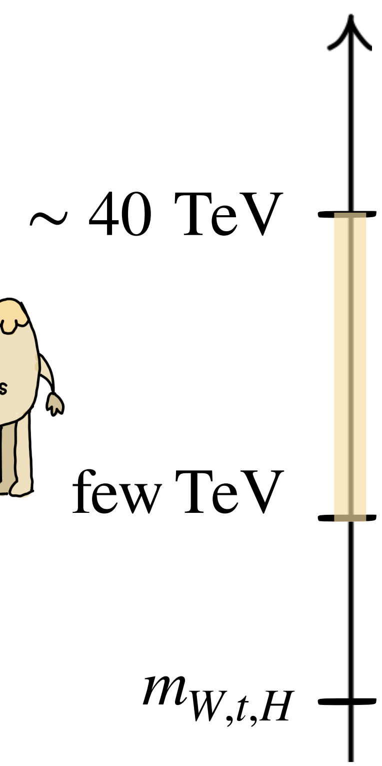
- Lorentz structure
  - New Physics in C_9^μ only, or
  - Left-handed NP: $\Delta C_9^\mu = -\Delta C_{10}^\mu$ (+ universal shift ΔC_9^U)

- Size (scale)



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



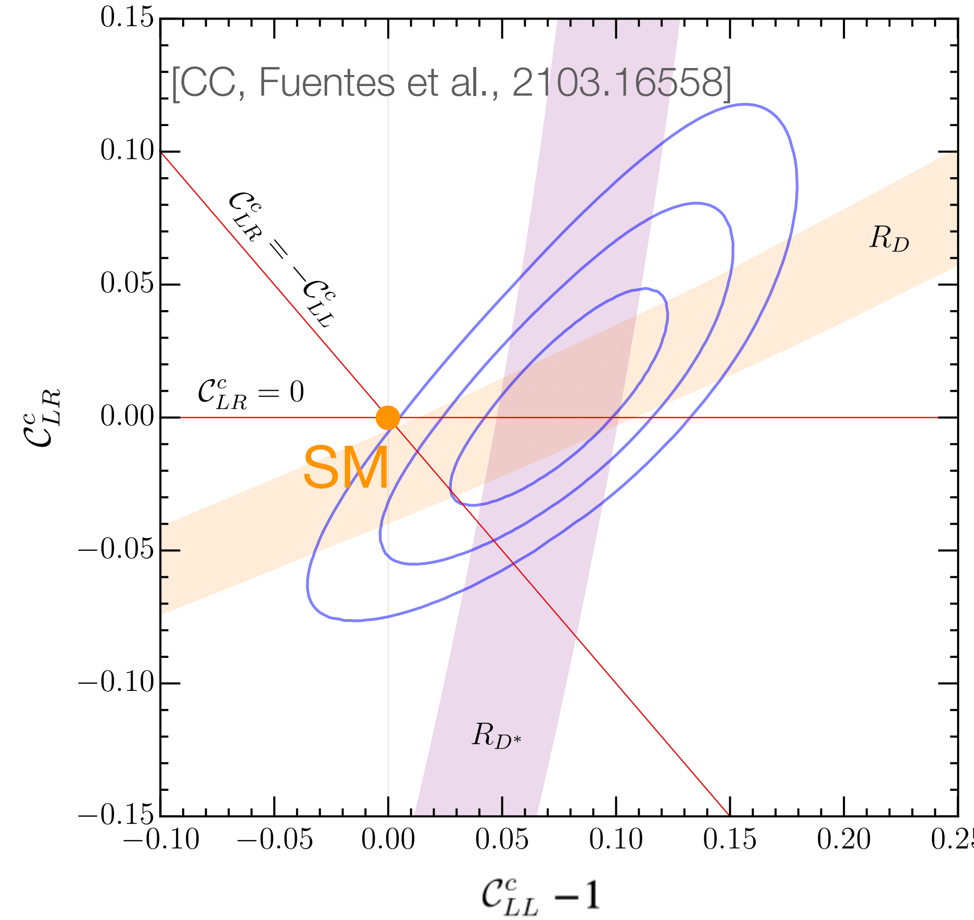


EFT for $b \to c\tau\nu$

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

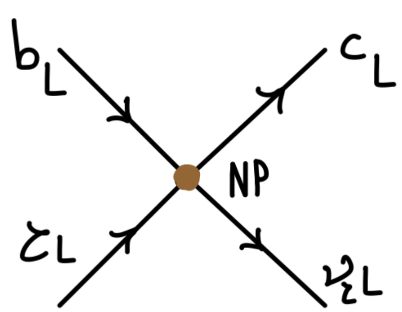
$$O^i_{LL} = (\bar{u}^i_L \gamma_\mu \nu_L)(\bar{\tau}_L \gamma^\mu b_L) \qquad C^{\text{SM}}_{LL} = 1$$

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

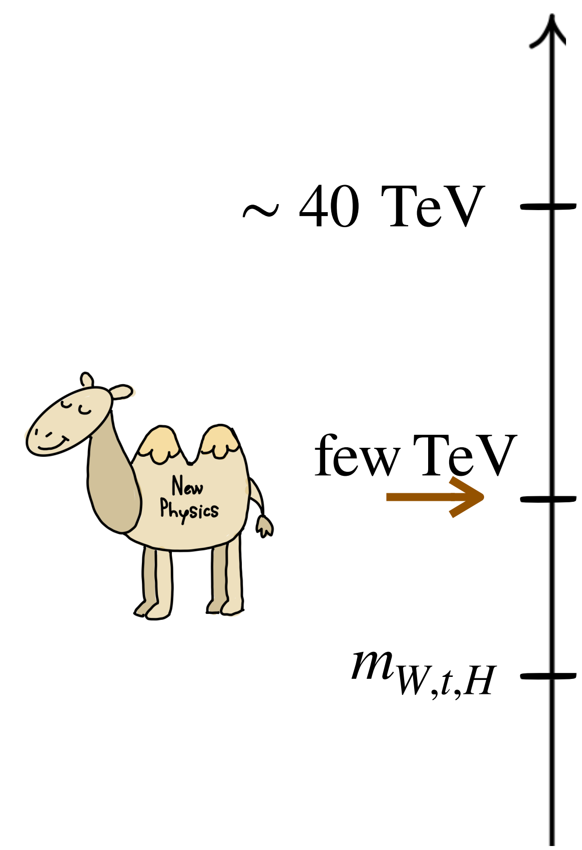


- Lorentz structure
  - left-handed NP (=Fermi interaction!)
  - other structures also possible

- Size (scale)



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



Why both?

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

$$b \to sll \qquad \xleftrightarrow{SU(2)_L} \qquad b \to cl\nu$$

$$(\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L) \qquad \qquad (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L)$$

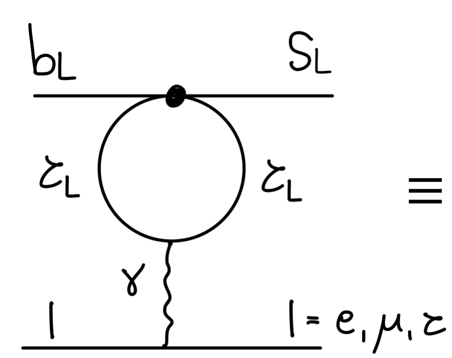
⇒ Minimal sol: **left-handed NP in semi-leptonic operators** (RH currents also possible)

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

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

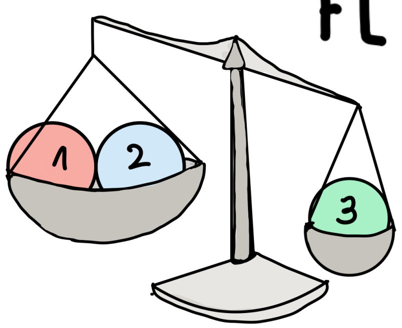
Connection between anomalies:

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



$$\equiv \Delta C_9^U$$

Why both?



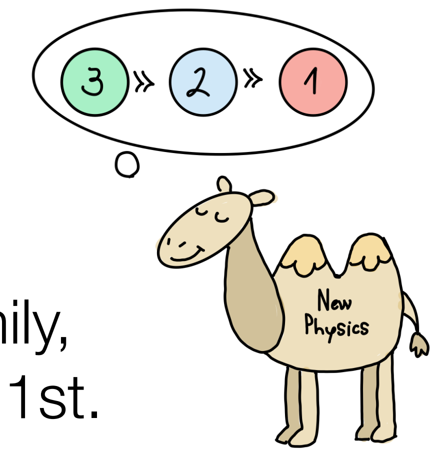
FLAVOR HIERARCHIES ? ⟷ **FLAVOR ANOMALIES**

standard LFUV

$y_3 \gg y_2 \gg y_1$

non-standard LFUV

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



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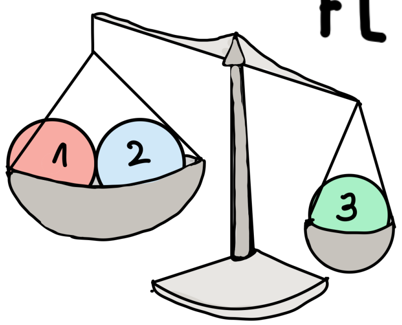

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$\overset{?}{\longleftrightarrow}$

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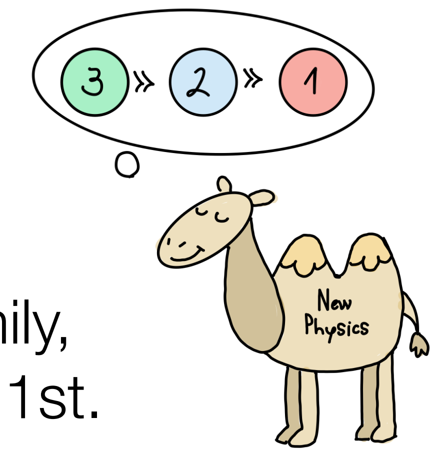

$$U(2)^5 = U(2)_q \times U(2)_l \times U(2)_u \times U(2)_d \times U(2)_e$$

$$\psi = (\boxed{\psi_1 \ \psi_2} \ \psi_3)$$

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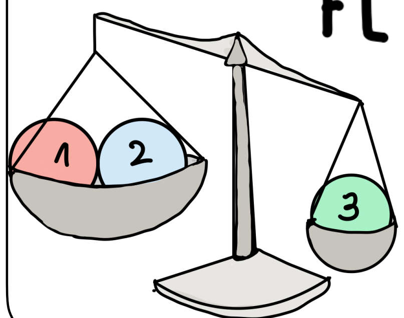

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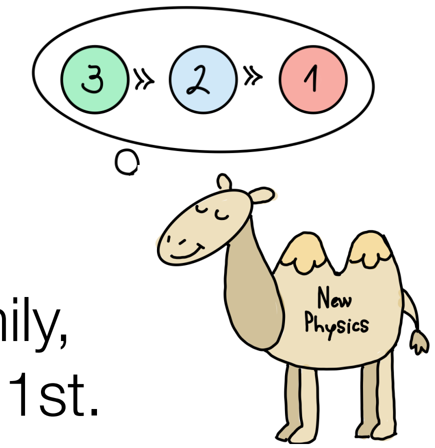

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$$\psi = \left((\psi_1 \ \psi_2) \ \psi_3 \right)$$

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

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

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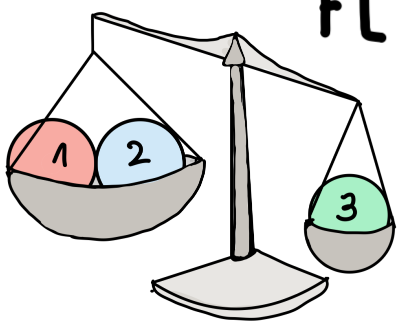

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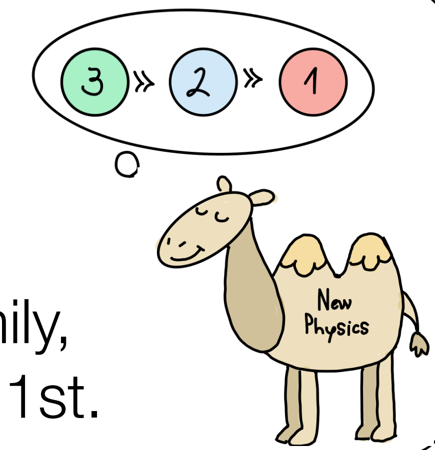

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SM masses & mixings, “flavored” alternative to MFV [Barbieri et al.,1105.3396]

Same pattern? [Barbieri et al.,1512.01560]

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minimally broken U(2)⁵

NP max for 3rd family, suppressed by $\epsilon_q\,(\epsilon_l)$ for each 2nd family quark (lepton)

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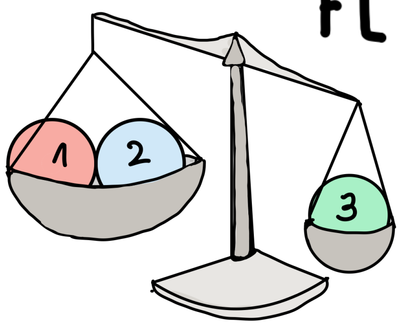

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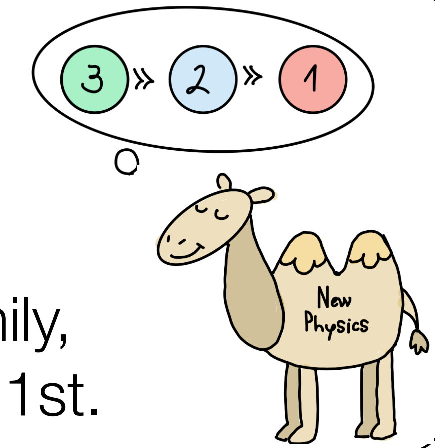

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EFT for combined explanations (LL)

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

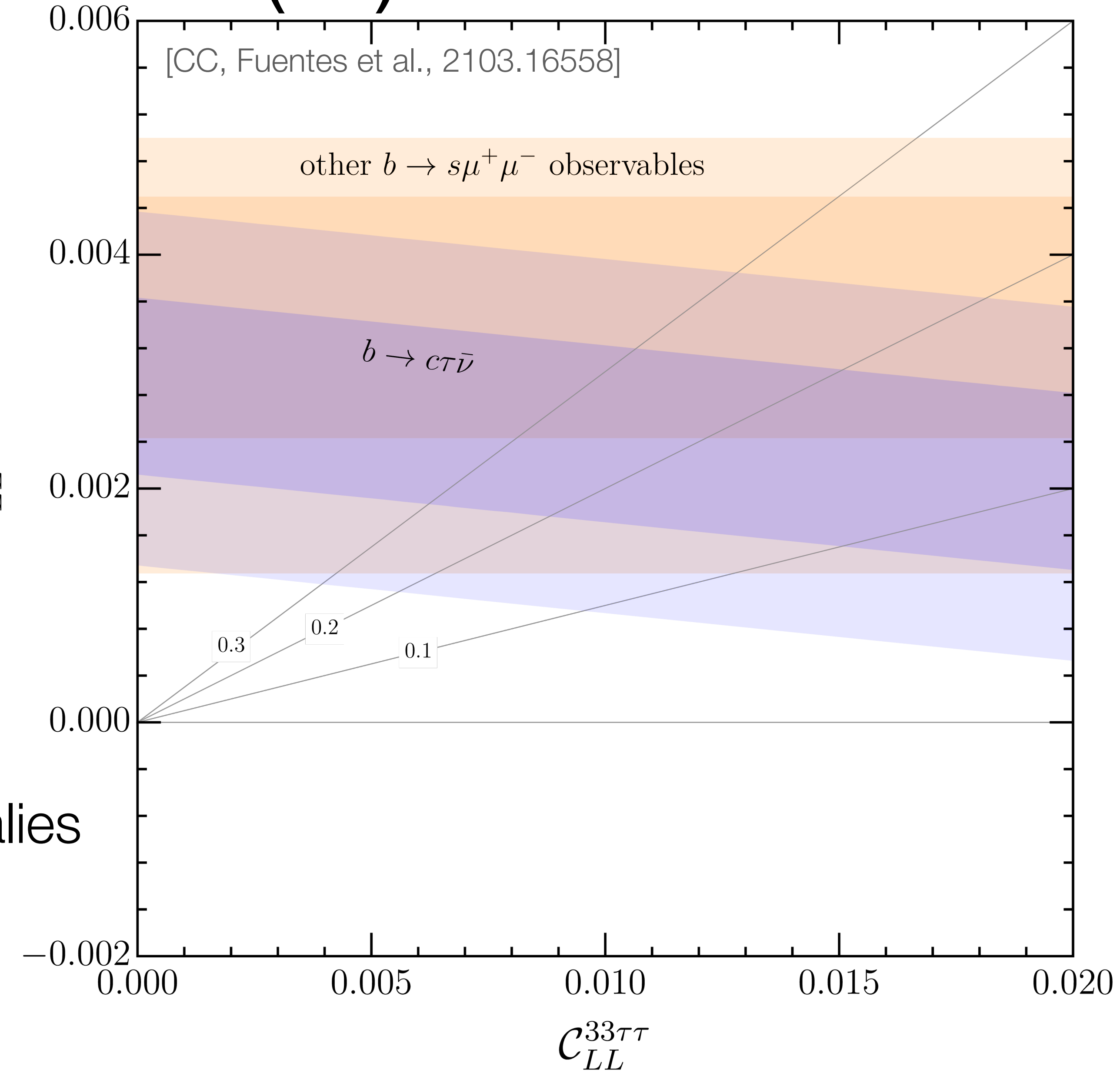
- Data support U(2) scaling,

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

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

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

- good consistency between the anomalies



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

[See Nudzeim's talk for more on LFU tests in τ decays]

EFT for combined explanations (LL)

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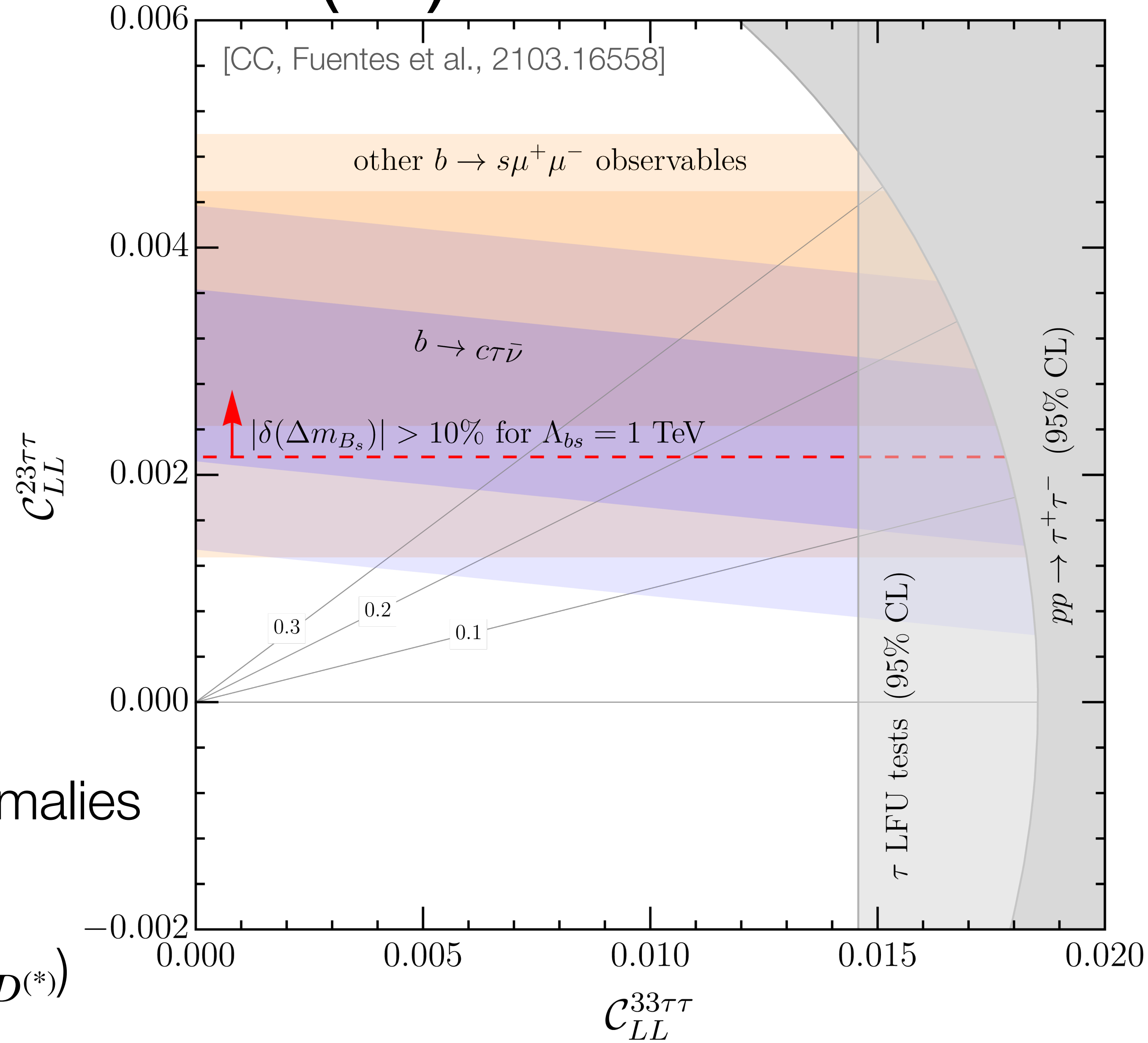
$b \to c$: $C_{LL}^{33\tau\tau} \sim 0.1$

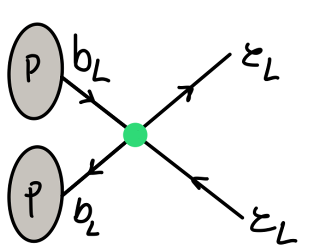
$b \to c$, $b \to s$: $C_{LL}^{23\tau\tau} \sim \epsilon_q C_{LL}^{33\tau\tau}$ $\qquad \epsilon_q, \epsilon_l \sim 0.1$

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

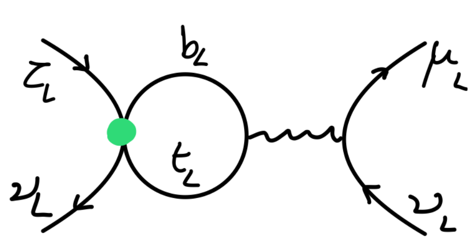


- good consistency between the anomalies

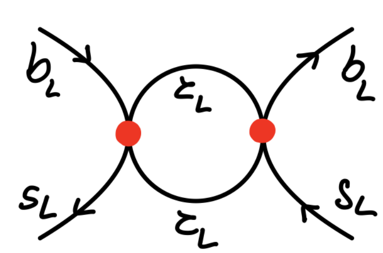
- but several constraints (driven by $R_{D^{(*)}}$)



$pp \to \tau\tau$



τ LFU tests



$B_s - \bar{B}_s$

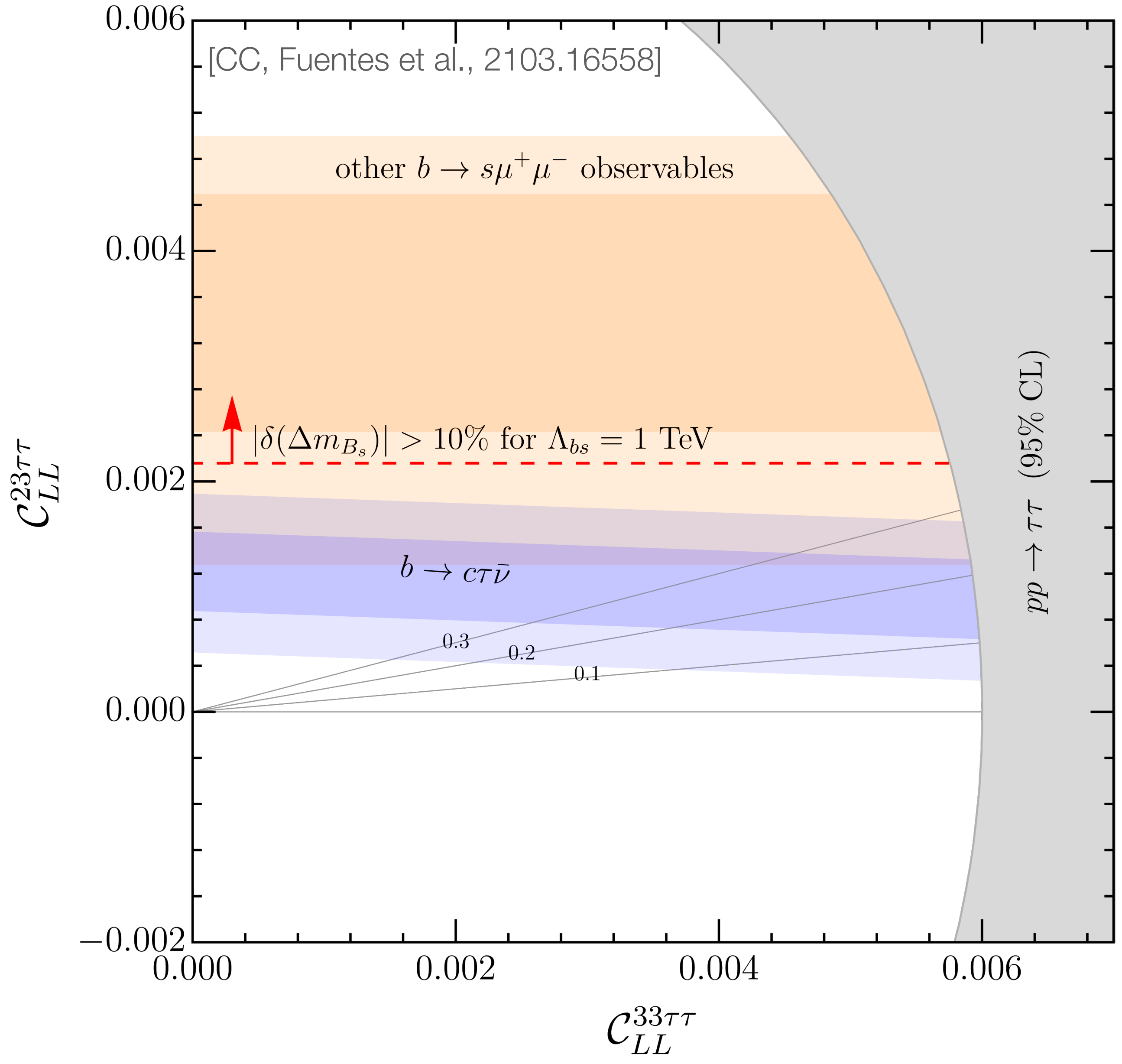
$$\frac{R_{D^{(*)}}}{R_{D^{(*)}}^{\rm SM}} - 1 = 2{\rm Re}\left(C_{LL}^{33\tau\tau} + \frac{V_{cs}}{V_{cb}} C_{LL}^{23\tau\tau}\right)$$

[See Nudzeim's talk for more on LFU tests in τ decays]

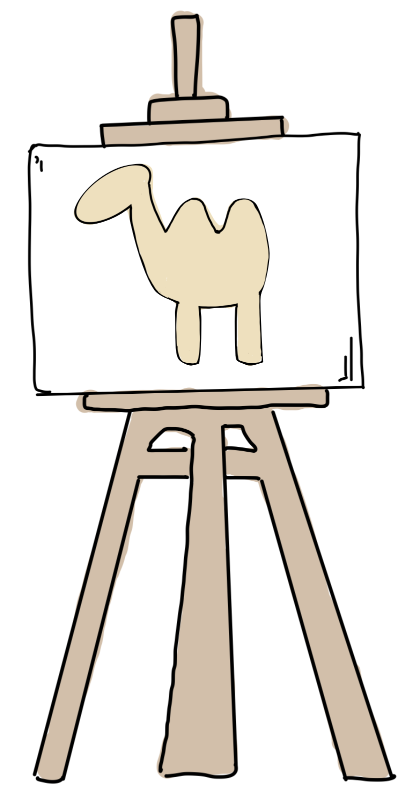
EFT for combined explanations (LL + LR)

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

- LR helps saturating $R_{D^{(*)}}$
  - $\to$ τ LFU and B_s-$\bar{B}_s$ less stringent.
- Both chiralities enter $pp \to \tau\tau$
  - $\to$ 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. 1706.0780 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]

[See also David's talk]

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.

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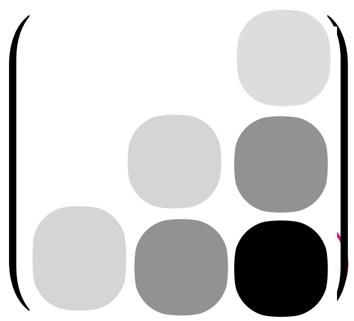
$\beta^L =$ 

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

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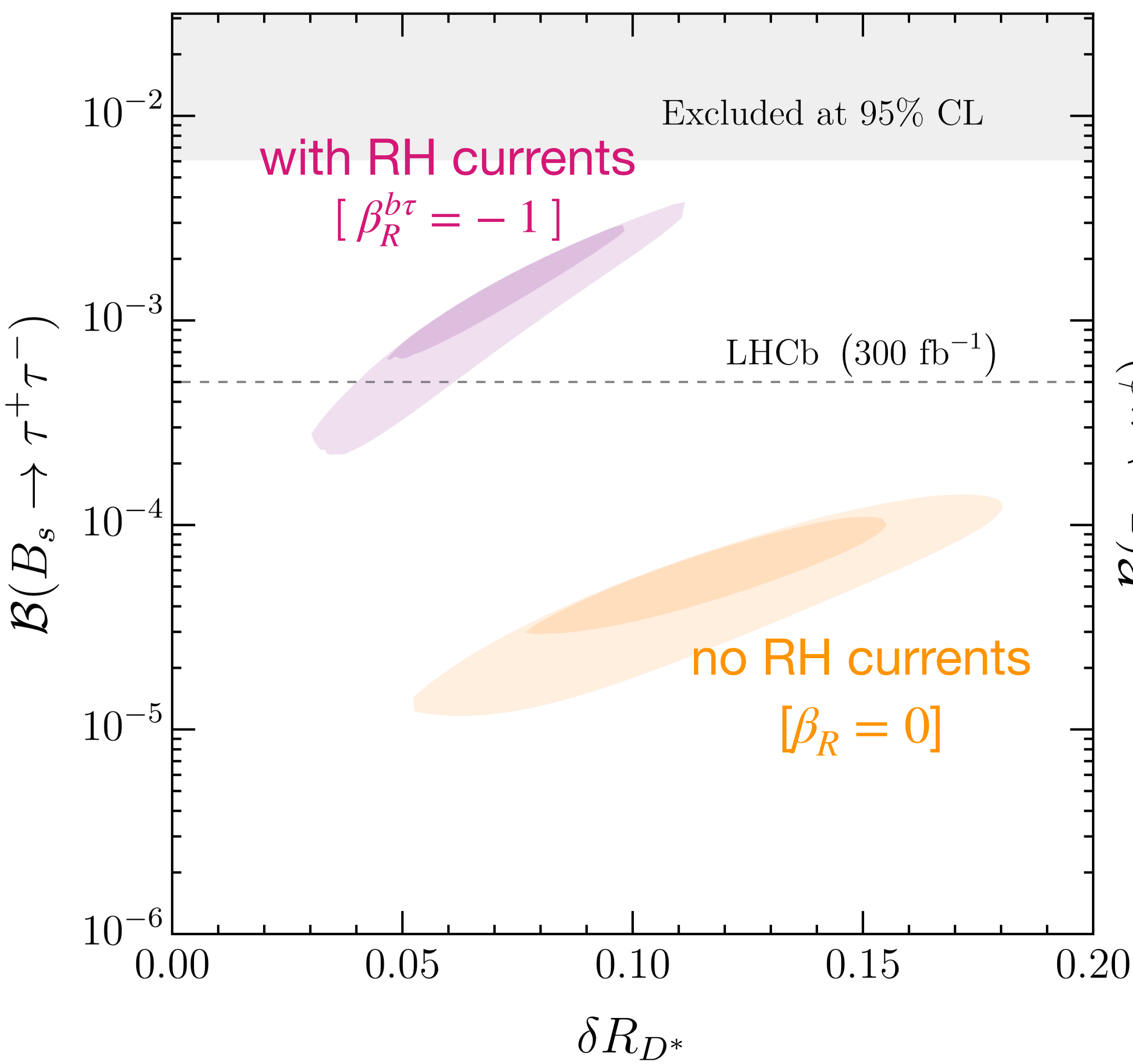
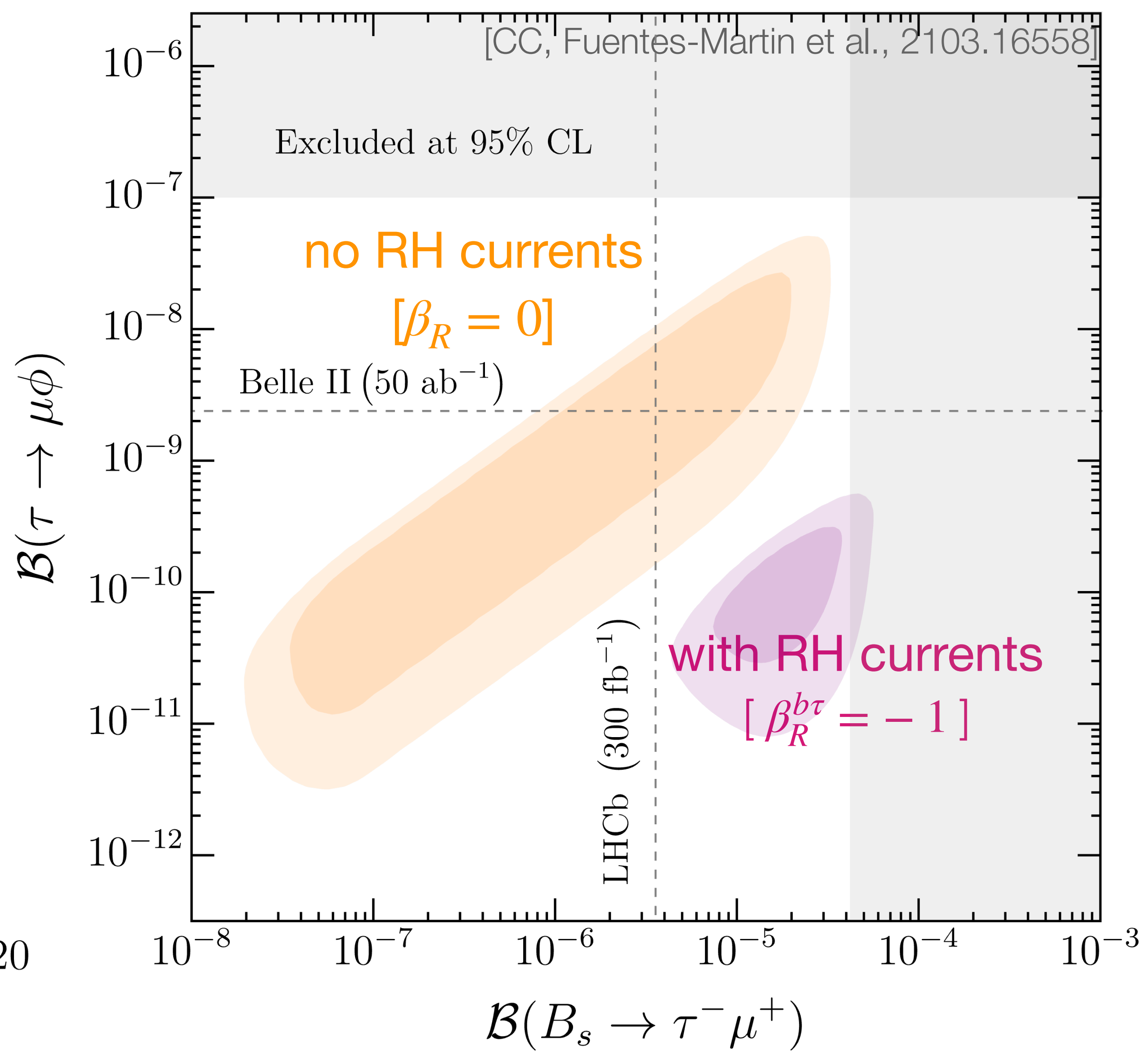
Low-energy predictions for the U_1

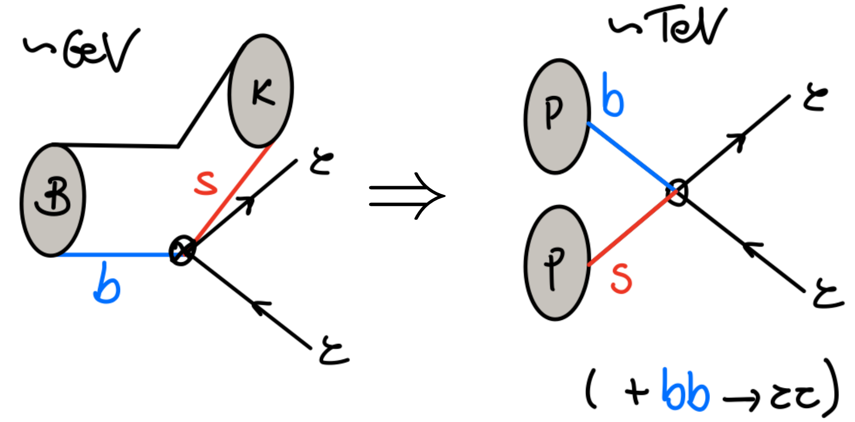
- large $b \to s\tau\tau$



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

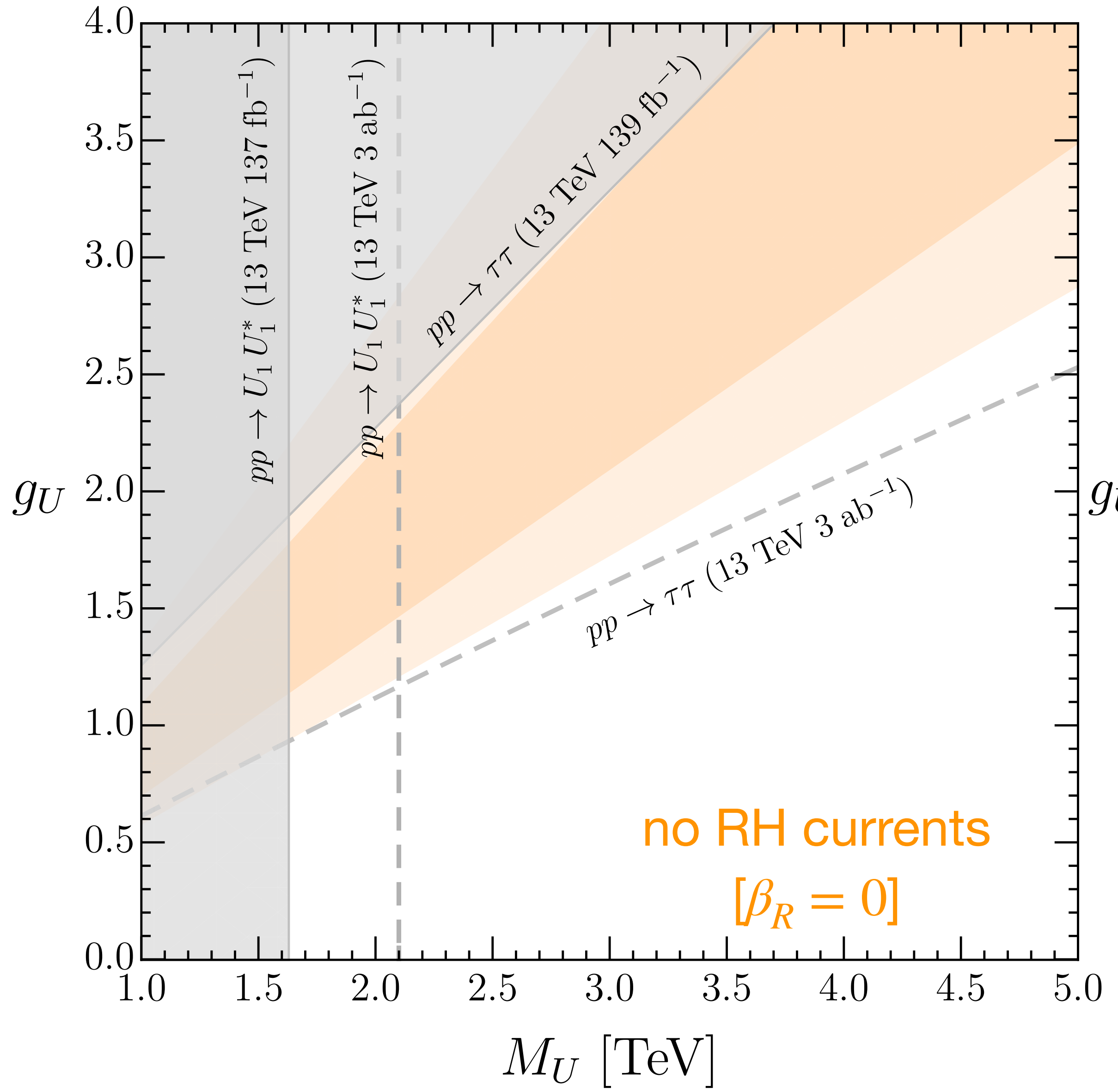


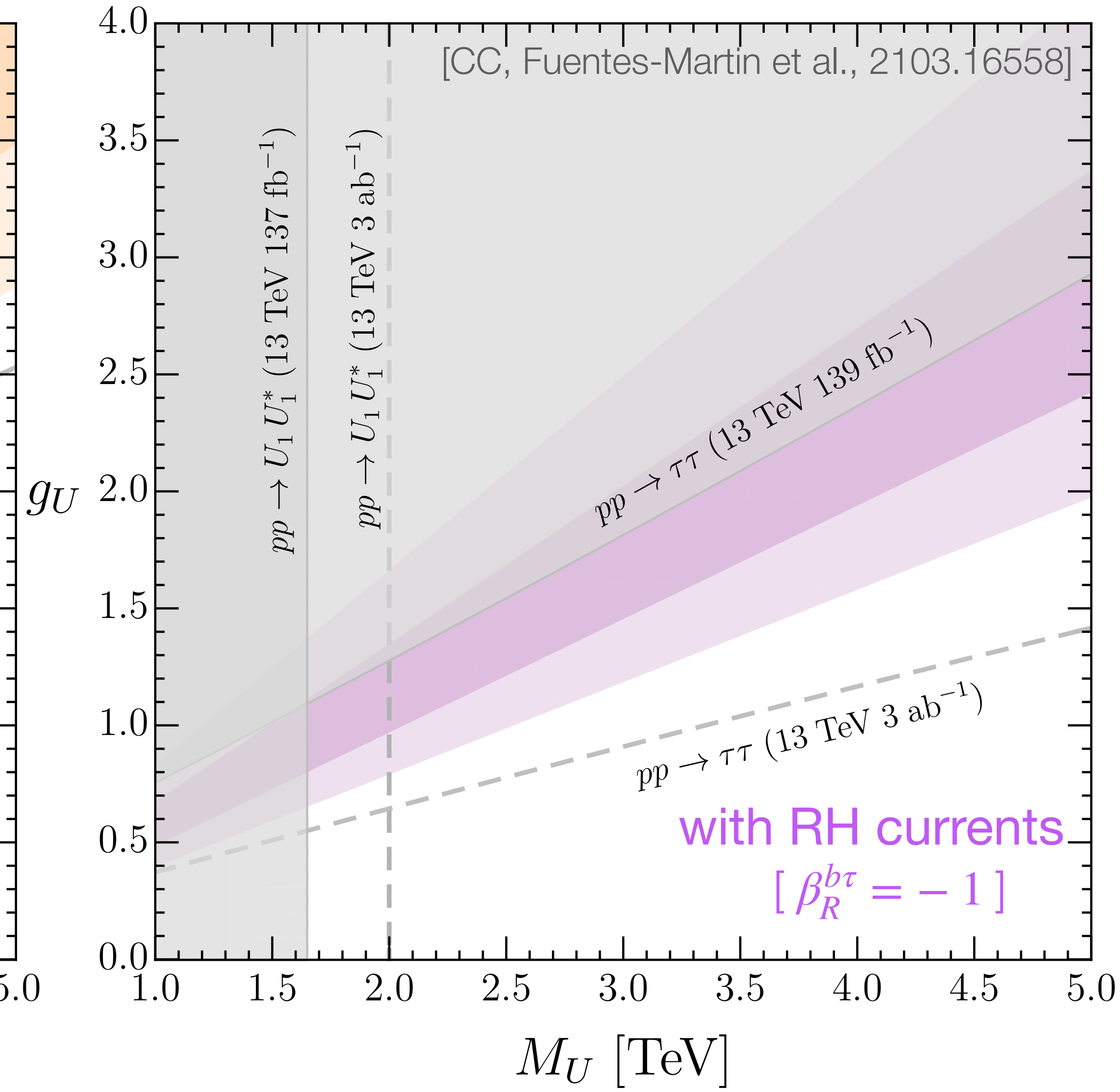
High-pT bounds for the U_1



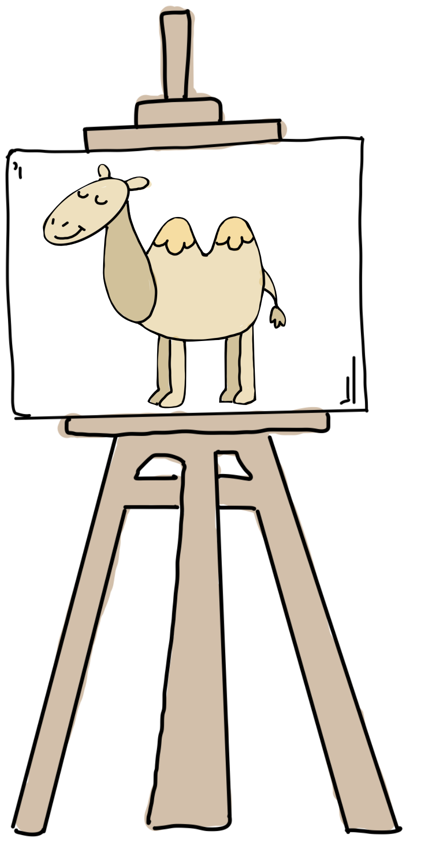
The same interaction can be probed in di-tau tails.

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

- ✓ $SU(4)$ 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]

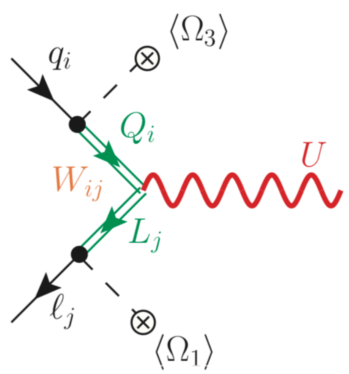
$$\mathcal{G}_{4321} = SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$$

$i = 1,2,3$ $\Psi = \begin{pmatrix} Q \\ L \end{pmatrix}$

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$	
$q_L'^i$	1	3	2	$1/6$	SM fields all families
$u_R'^i$	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	vectorlike fermions
Ψ_R^i	4	1	2	0	
H	1	1	2	$1/2$	scalar sector
Ω_3	$\bar{4}$	3	1	$1/6$	
Ω_1	$\bar{4}$	1	1	$-1/2$	

- **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

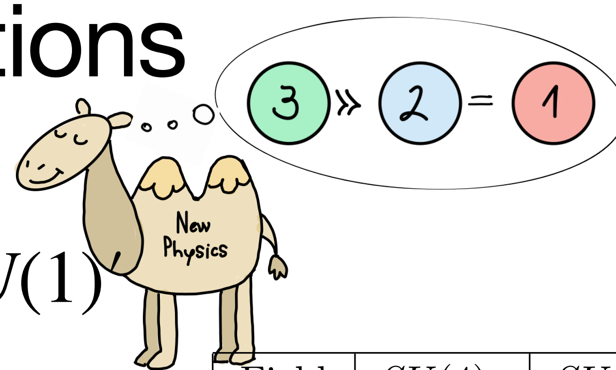
  → 3rd family has to be the "*most composite*"

- 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**

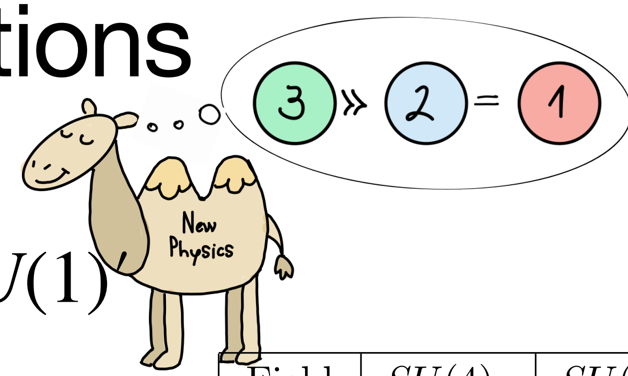
- light SM families: SM-like charges under 321
- vectorlike fermions and 3rd SM family charged under 4

  - 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	$SU(4)_3$	$SU(3)_{1+2}$	$SU(2)_L$	$U(1)_{Y'}$	
q_L^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	SM fields: 1st & 2nd family
u_R^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	
d_R^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	
ℓ_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	vectorlike fermions
χ_R^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0	
H	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	scalar sector
Ω_1	$\bar{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$	
Ω_3	$\bar{\mathbf{4}}$	$\mathbf{3}$	$\mathbf{1}$	$1/6$	
Ω_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$	0	

Non-universal gauge interactions



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

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$i = 1,2$

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	
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Ω_1	$\bar{\mathbf{4}}$	**1**	**1**	$-1/2$	
Ω_3	$\bar{\mathbf{4}}$	**3**	**1**	$1/6$	
Ω_{15}	**15**	**1**	**1**	0	

- **$U(2)^5$ 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:

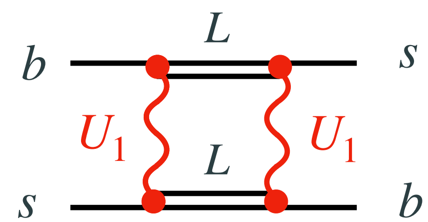
constrained by $K_L \to \mu e$, K-$\bar{K}$ and D-$\bar{D}$

*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]

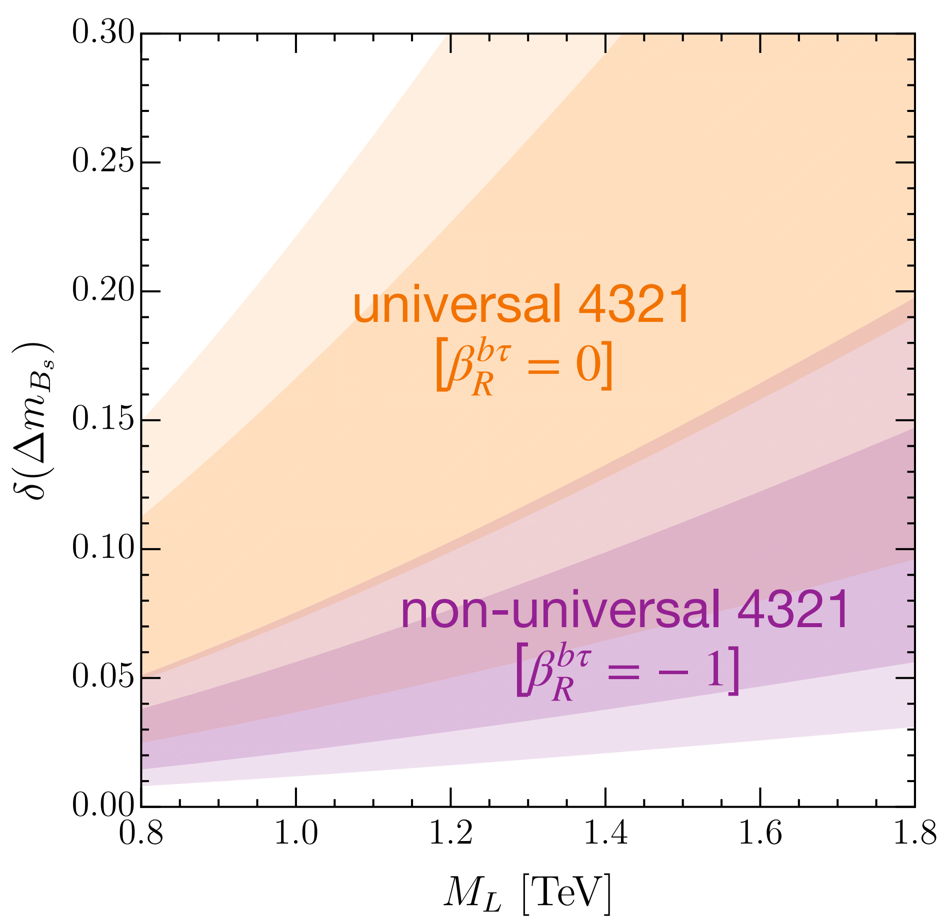
- B_s-$\bar{B}_s$ mixing



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

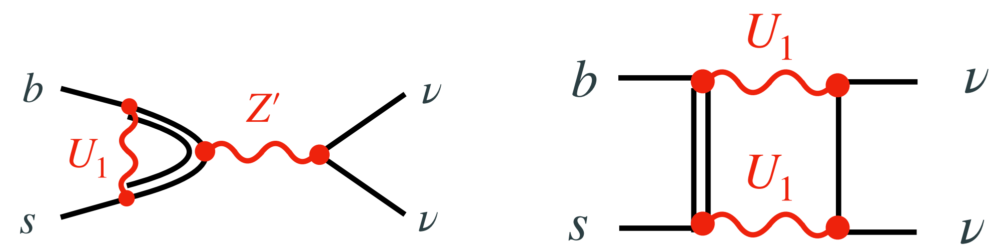
$\dashrightarrow U(2)_q$ breaking (for $R_{D^{(*)}}$)

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

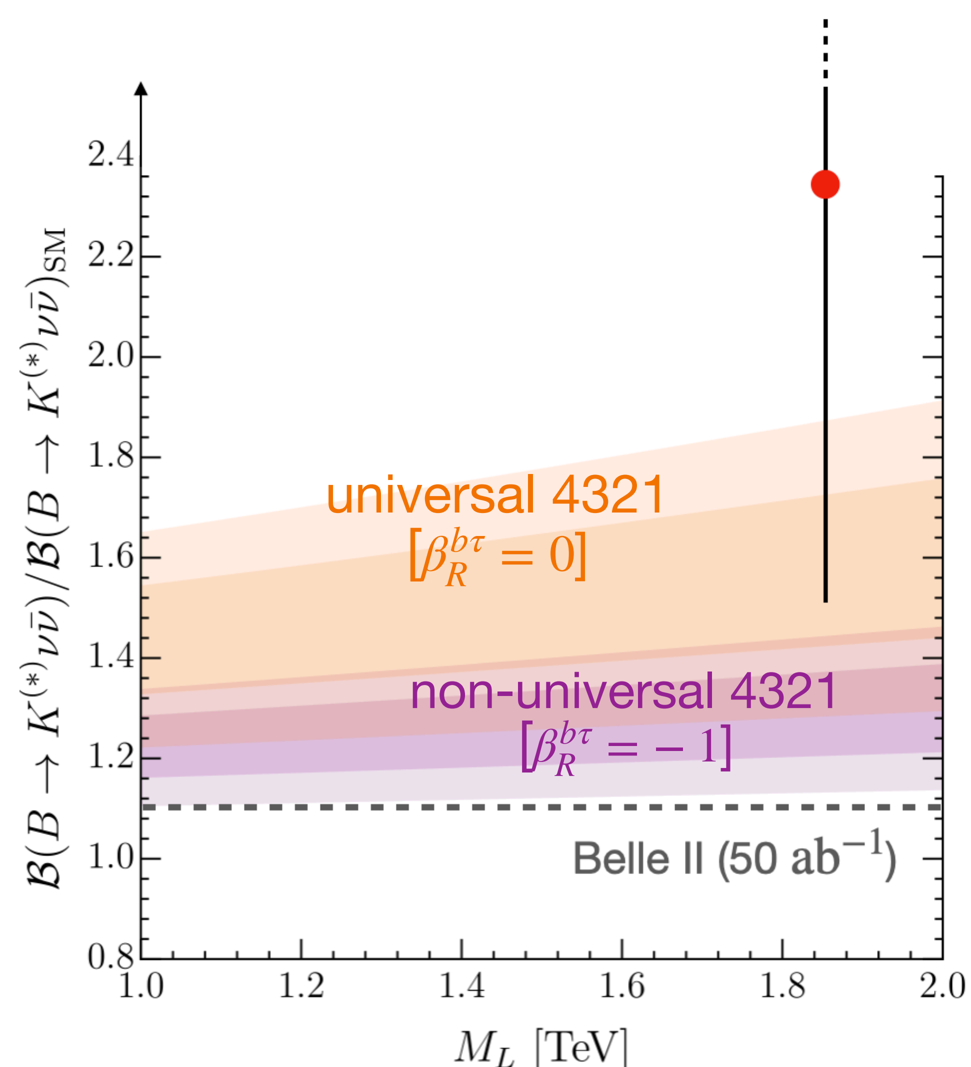


- $B \to K\nu\bar{\nu}$

[Nudzeim's talk for LFU tests in τ decays]



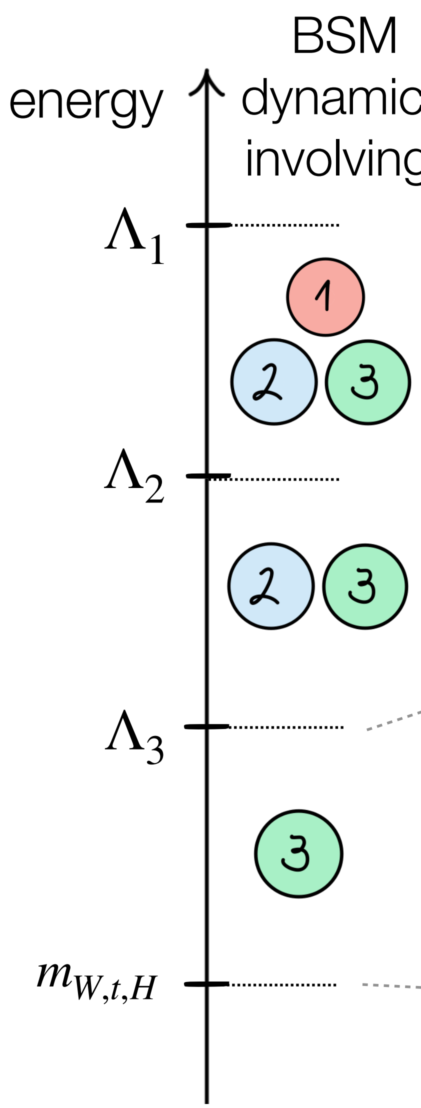
→ 20-50% enhancement over the SM (also driven by $R_{D^{(*)}}$), in the reach of Belle II



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:

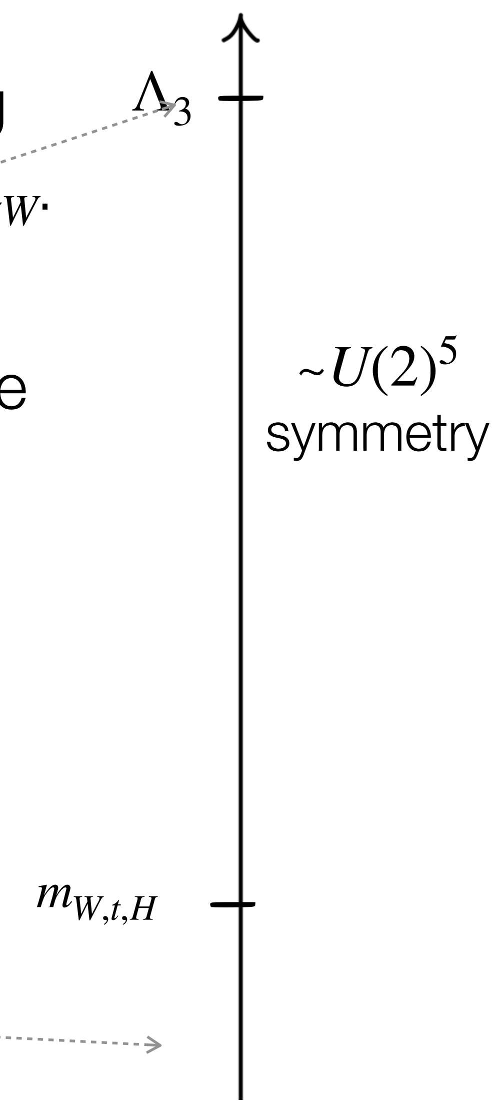


New, non-universal interactions (for us: gauge) acting on the i-th SM family switch on at $\Lambda_1 \gg \Lambda_2 \gg \Lambda_3 \gg m_W$.

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

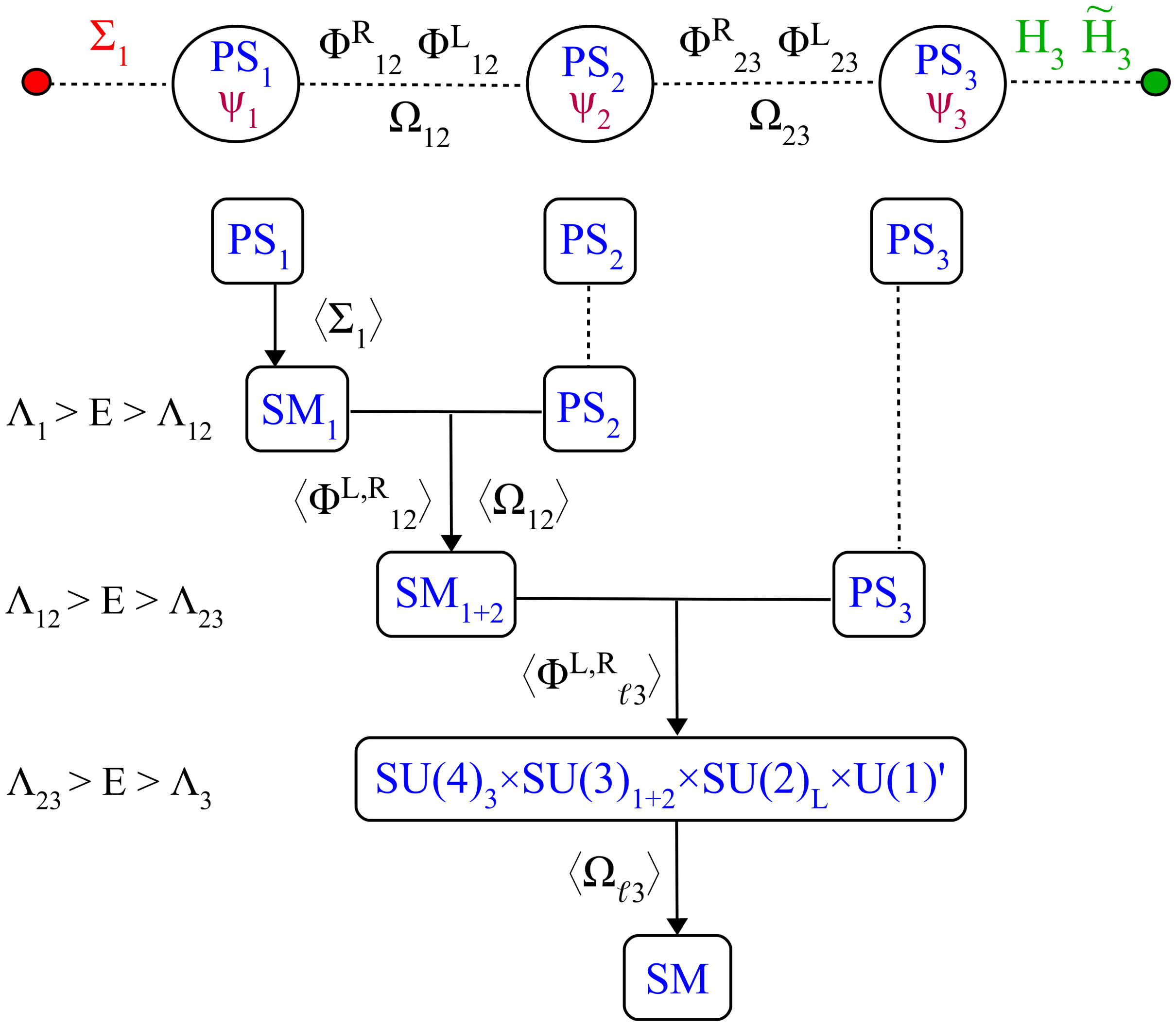
New Physics is flavor non-universal; universality is a low-energy accident.

Λ_3 can be as low as few TeV.



Non-universal Pati-Salam unification

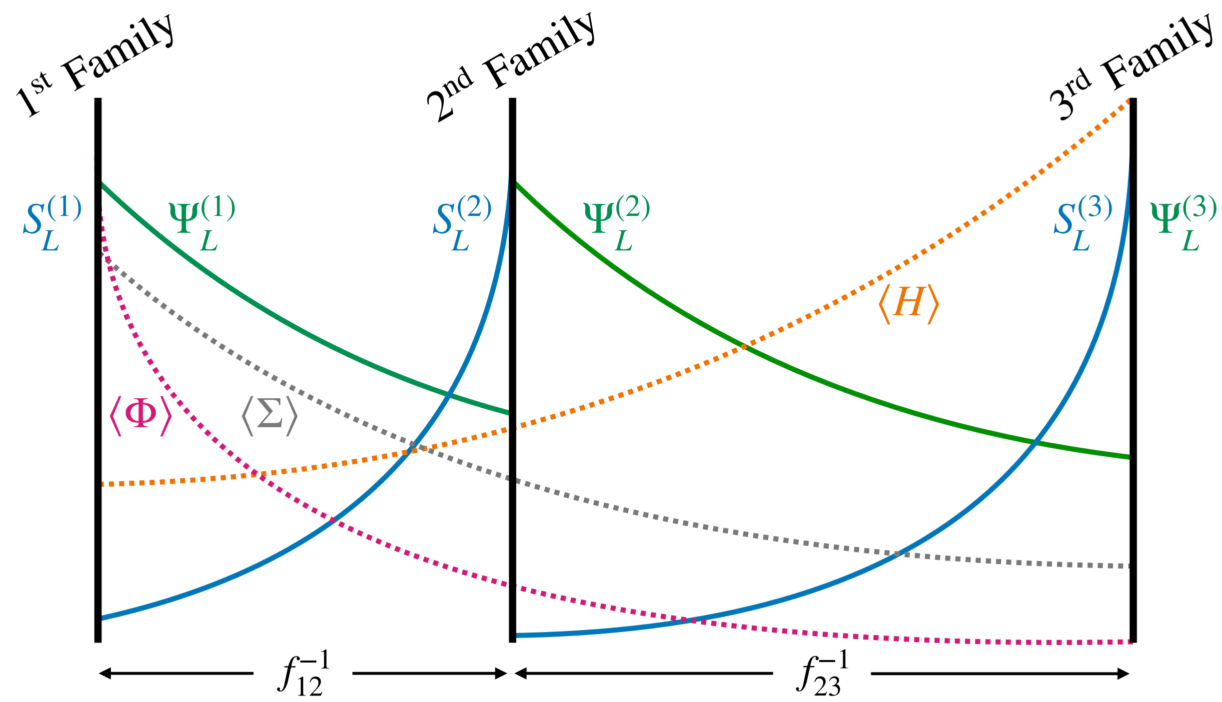
- **PS³: 4D three-site model**



[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, 2203.01952]

A lot more in Ben's talk on Friday!

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.

- 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 guidance!

- 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?