Combined explanations of B-physics Anomalies: from Data to New Physics Models

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Reading the footprints of the B anomalies

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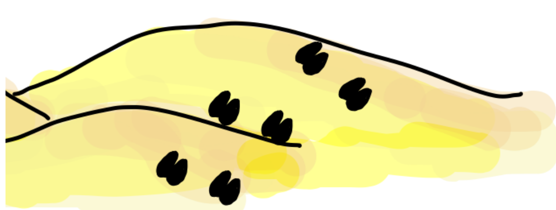
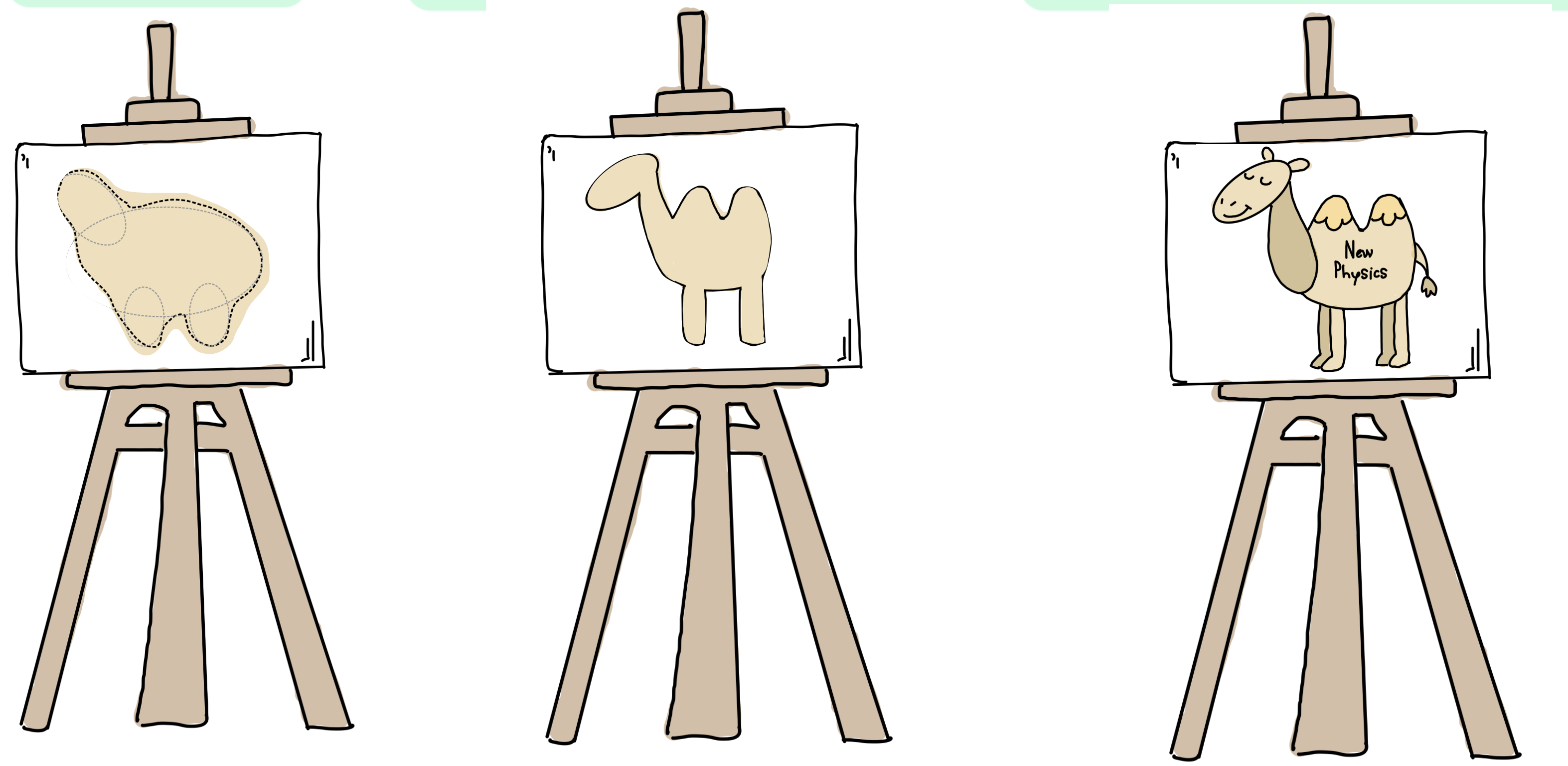
Usual strategy:

DATA → EFT → SIMPLIFIED MODEL → UV COMPLETION

$b \to sll$
$b \to c\tau\nu$





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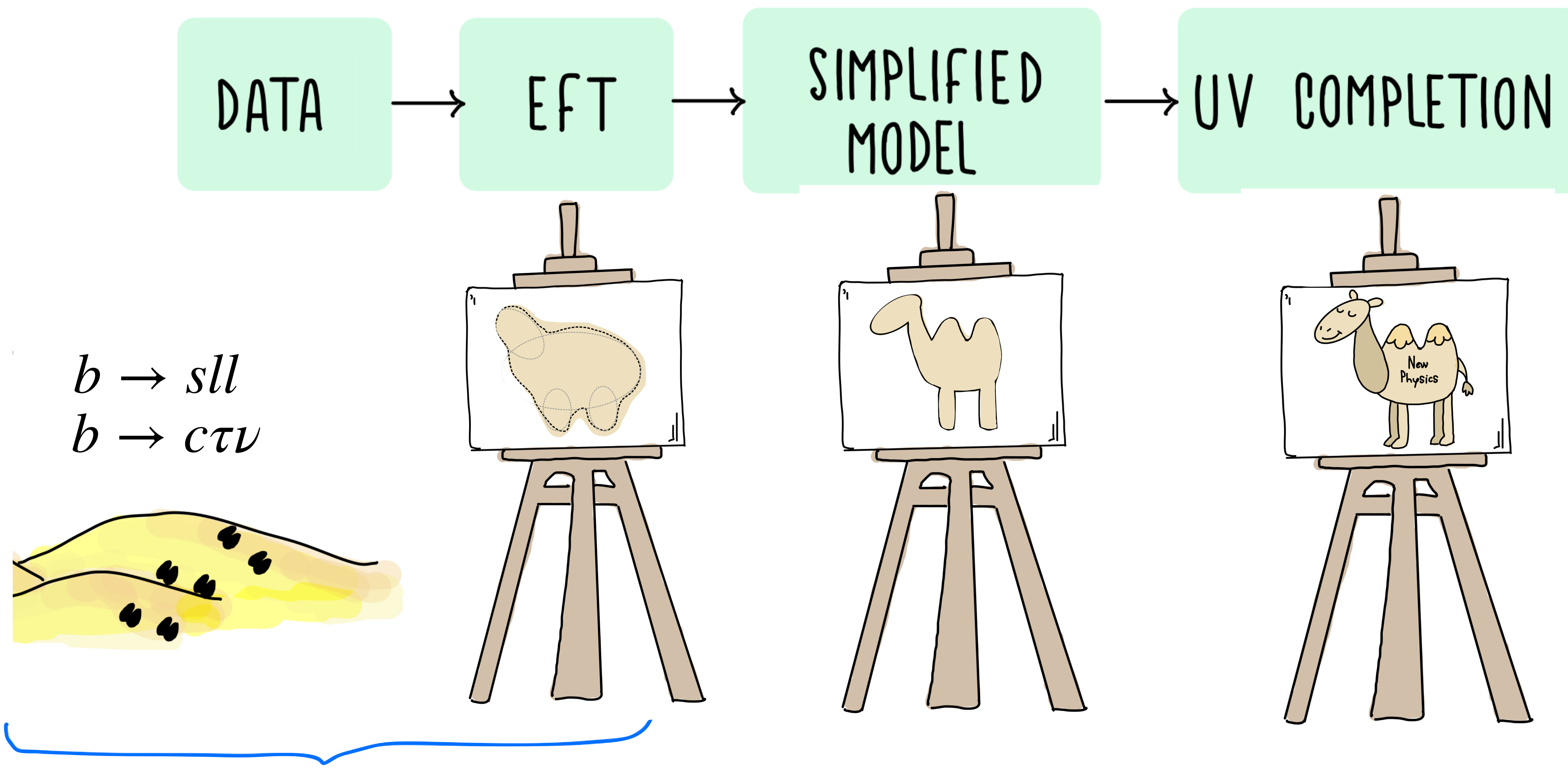

[Sally, Eluned, Guy,]

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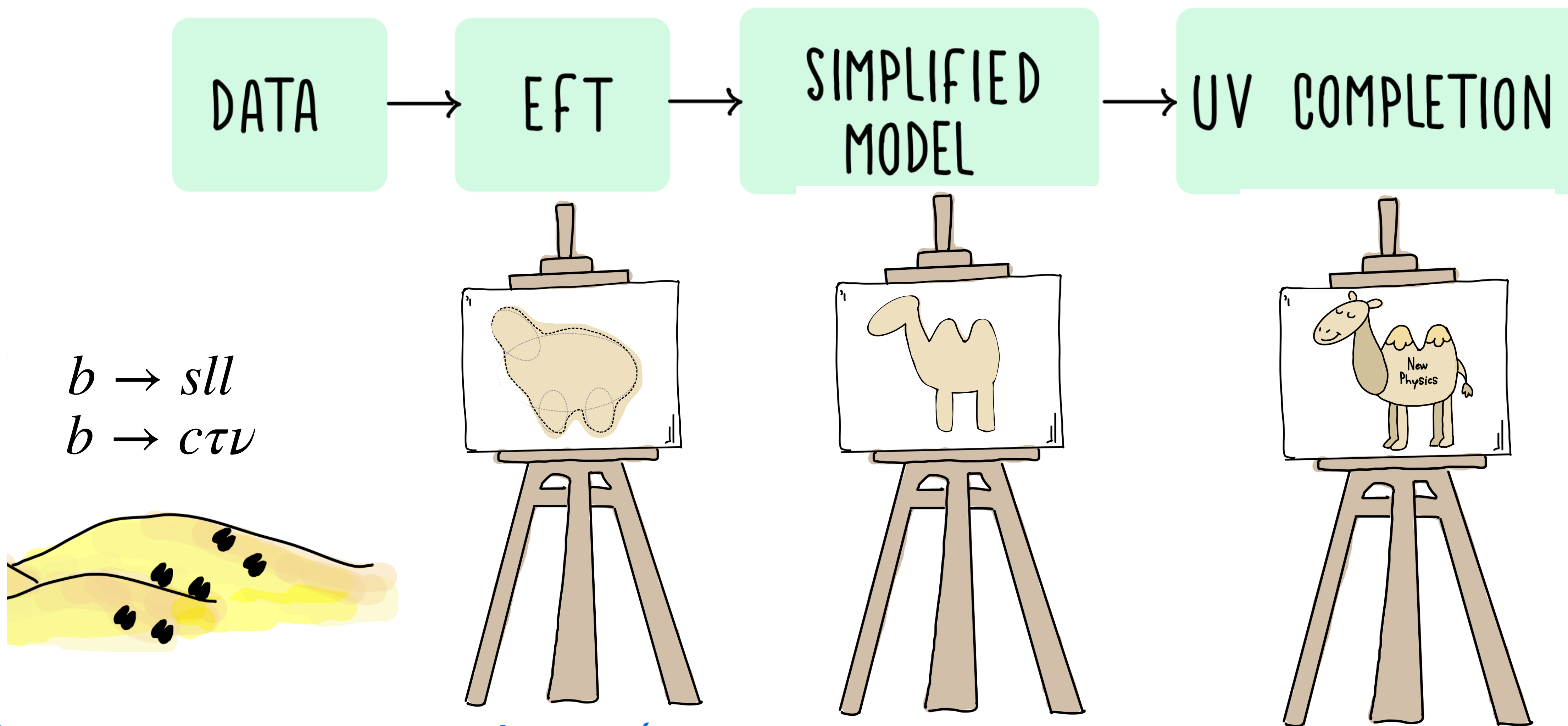

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this talk

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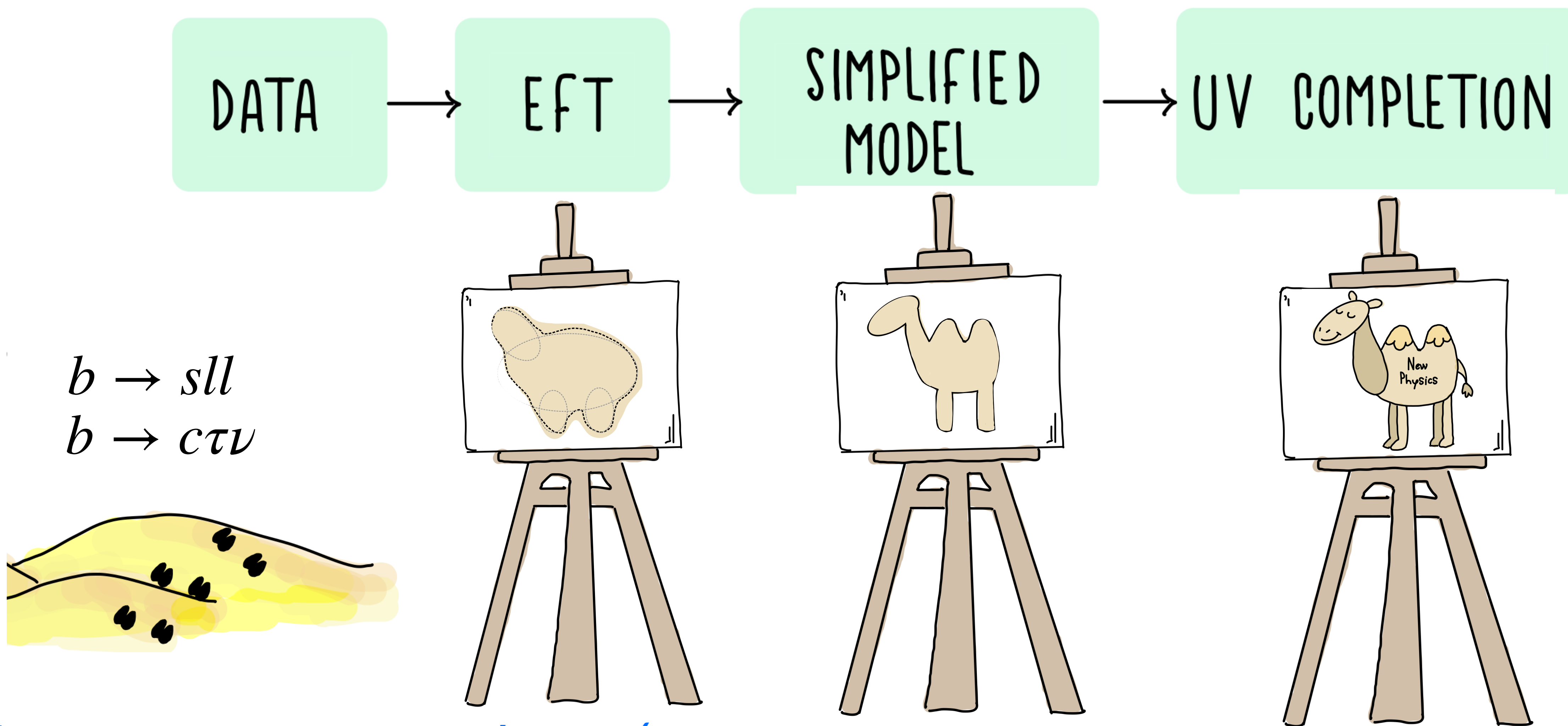

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this talk

[many other talks: **Ben, Julie**, Luc, Claudio, Maria, Yi…]

About camels and monkeys

[Photo by Julie Pages]

Given our weekend activities, I was suggested to turn the New Physics camel into a monkey.

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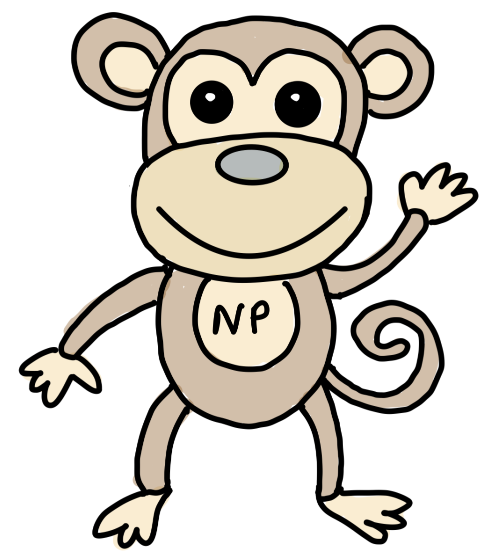

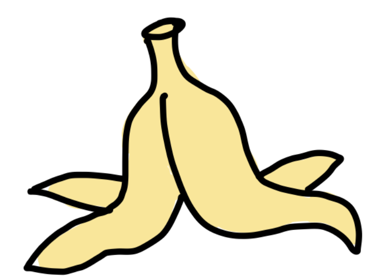

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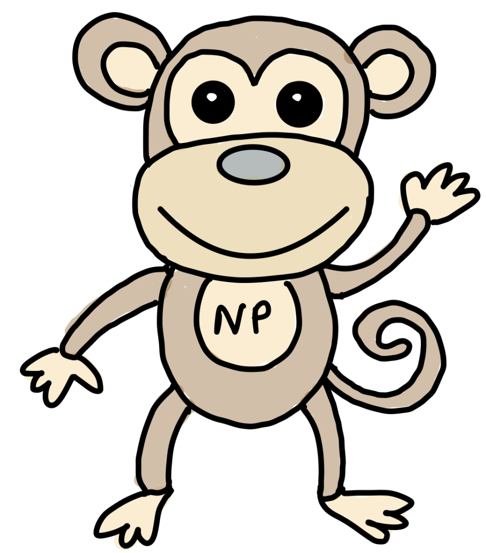
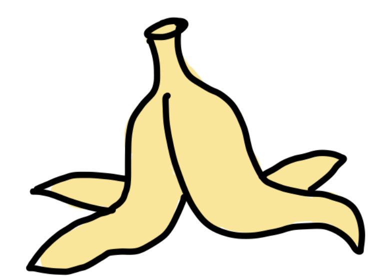
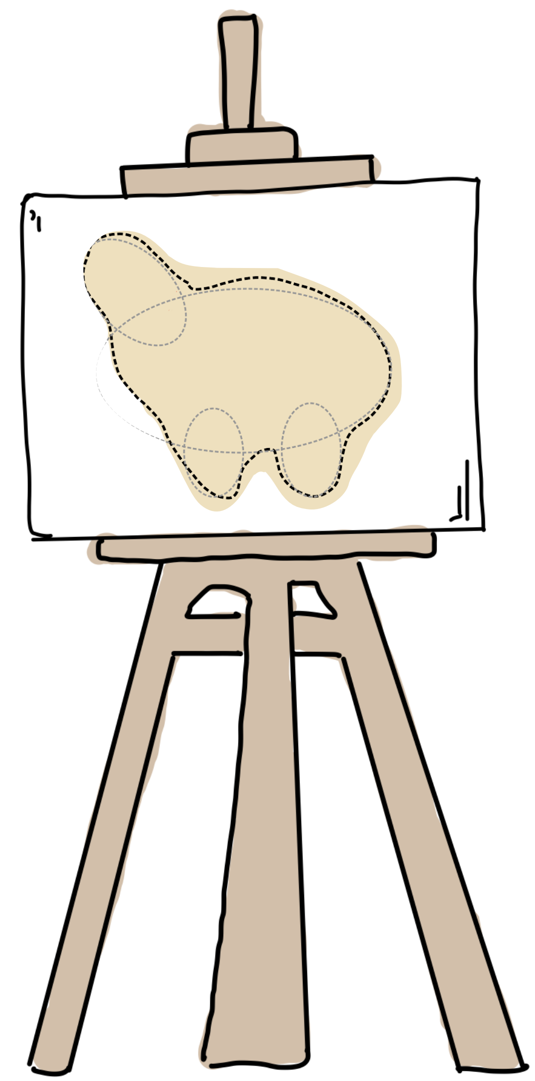




…too much work! Next time.

NP interpretation (I): Effective Theory



EFT lessons

EFTs provide a simplified, yet powerful, model-independent parametrization of NP contributions to observables. Lots to learn from an EFT analysis:

- **NP Lorentz structure**

- **NP size (scale)**

- **Flavor structure, correlations with other observables**

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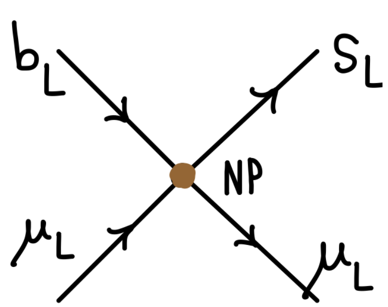
- **NP Lorentz structure**

$$b \to sll$$

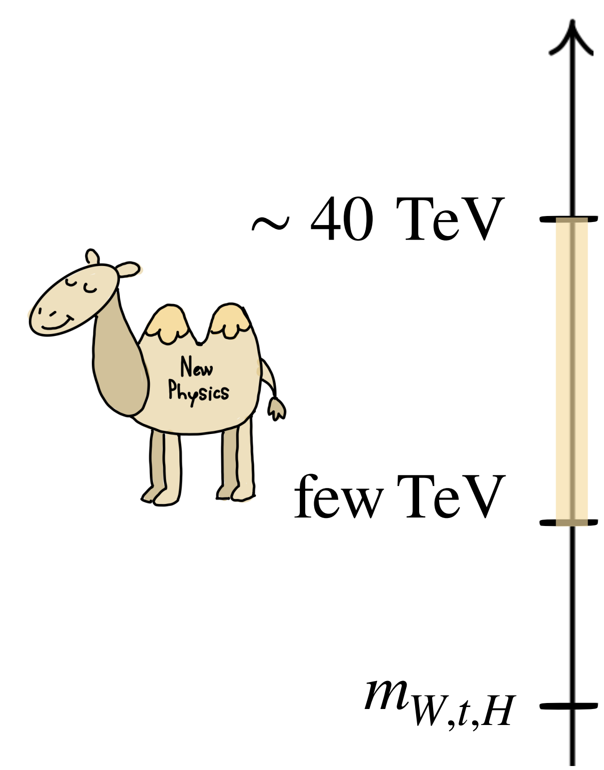
  - New Physics in C_9^μ only, or
  - Left-handed NP $\Delta C_9^\mu = -\Delta C_{10}^\mu$

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

- **NP size (scale)**



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



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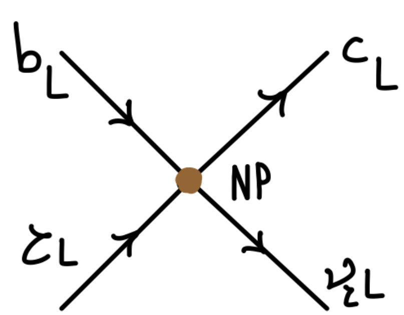
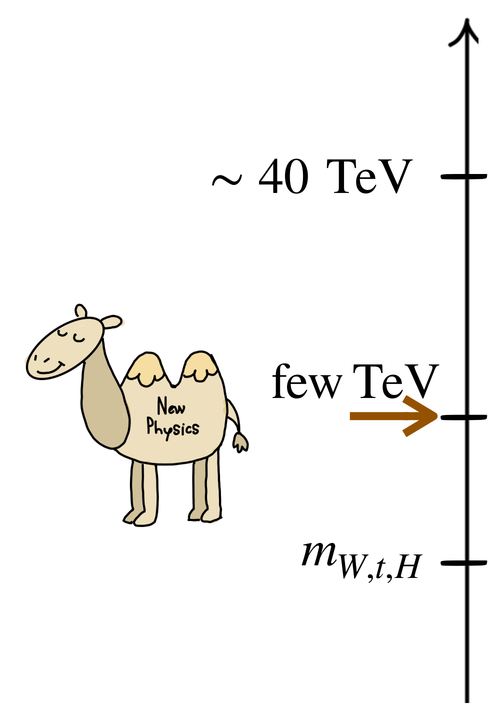
$b \to c l \nu$

- **NP Lorentz structure**
  - Left-handed NP (=Fermi interaction) $O_{V_L} = (\bar{c}_L \gamma_\mu \nu_L)(\bar{\tau}_L \gamma^\mu b_L)$
  - other structures are also possible

- **NP size (scale)**



$$\sim 10^{-2}\, G_F \quad \Rightarrow \quad \frac{g_{\rm NP}^2}{\Lambda^2} \sim \frac{1}{(1\ \mathrm{TeV})^2}$$



- **Flavor structure, correlations with other observables**

Possibile common origin

$SU(2)_L$ symmetry relates the structures we identified:

$$b \to sll \qquad\qquad b \to cl\nu$$

$$O_{9-10} = (\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L) \quad \overset{SU(2)_L}{\longleftrightarrow} \quad O_{V_L} = (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L)$$

→ a minimal combined solution in the SMEFT is obtained assuming NP to affect dominantly **left-handed, semi-leptonic operators**:

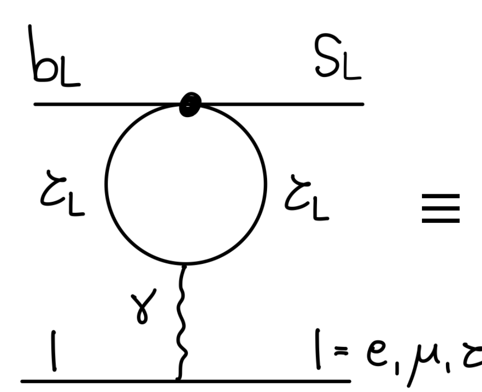
$$\mathscr{L} = -\frac{1}{v^2}\left(C^{(3)}_{\ell q}(\bar{\ell}_L \gamma^\mu \tau^a \ell_L)\left(\bar{q}_L \gamma^\mu \tau^a q_L\right) C^{(1)}_{\ell q}\left(\bar{\ell}_L \gamma^\mu \ell_L)(\bar{q}_L \gamma^\mu q_L\right)\right) \approx -\frac{2}{v^2} C_{LL}\left(\bar{q}_L \gamma^\mu l_L\right)\left(\bar{l}_L \gamma_\mu q_L\right)$$

! $b \to s\nu_{(\tau)}\bar{\nu}_{(\tau)}$ requires $C^{(3)}_{\ell q} \approx C^{(1)}_{\ell q}$

(automatically satisfied for U_1, needs to be enforced otherwise)

Connection between anomalies:

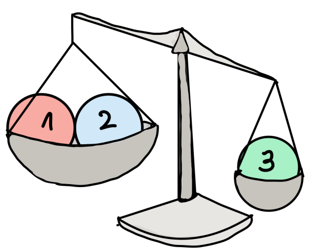
$$R_{D^{(*)}} \;\Rightarrow\; b_L \to c_L \tau_L \nu_L \;\overset{SU(2)_L}{\sim}\; b_L \to s_L \tau_L \tau_L \;\overset{\text{RGE}}{\Rightarrow}$$



$$\equiv \Delta C_9^U$$

Possibile common origin

- Also, need a peculiar **flavor structure**: large NP couplings to 3rd family, smaller to 2nd and 1st. Similar to the only SM source of LFUV, the Yukawa couplings!



FLAVOR HIERARCHIES

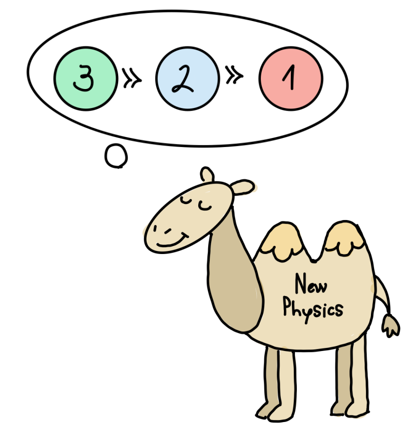
standard LFUV

$y_3 \gg y_2 \gg y_1$

?
$\longleftrightarrow$

FLAVOR ANOMALIES

non-standard LFUV



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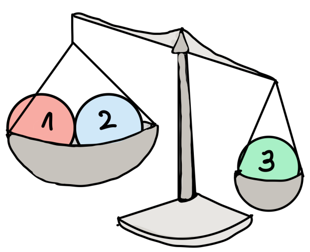

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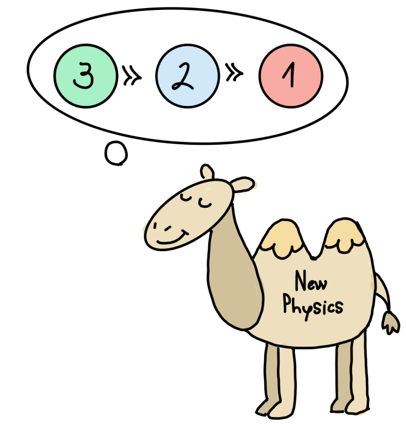

- Possible to describe both with the same **flavor symmetry:**

[Barbieri et al.,1105.3396, 1512.01560…]

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

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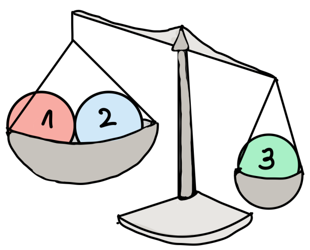

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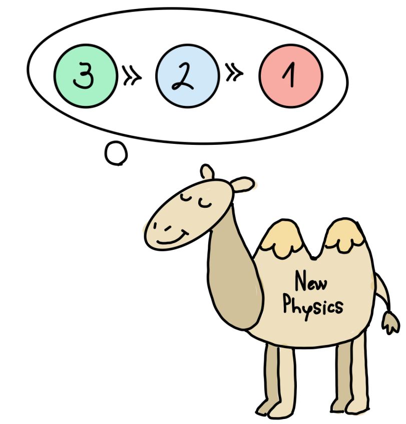

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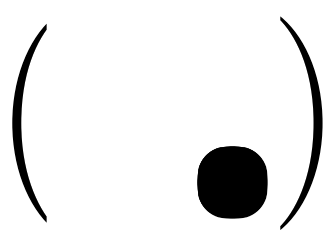
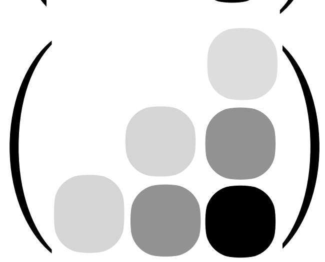
Works for SM masses & mixings…

$Y =$ 

exact U(2)^5

$Y =$ 

minimally broken U(2)^5

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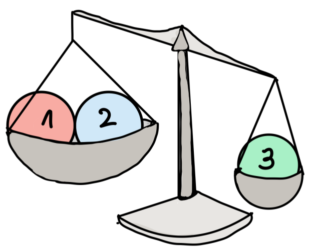

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FLAVOR ANOMALIES

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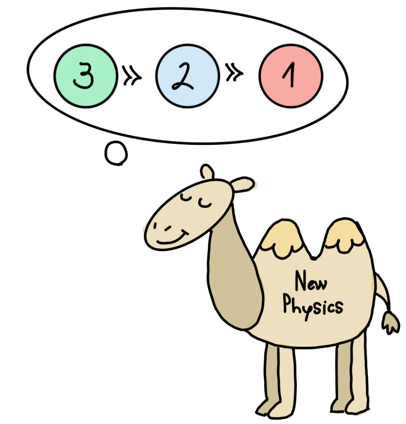

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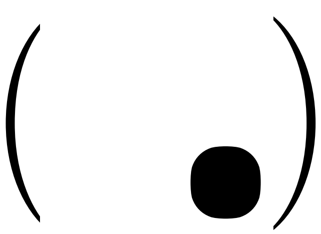
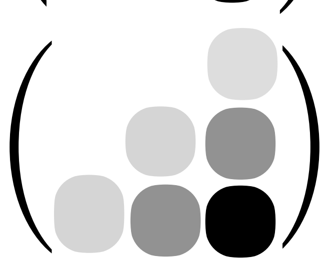
$Y =$ 

exact U(2)⁵

NP coupled only to 3rd family

$Y =$ 

minimally broken U(2)⁵

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

Possibile common origin

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

- Data support a U(2)-like scaling:

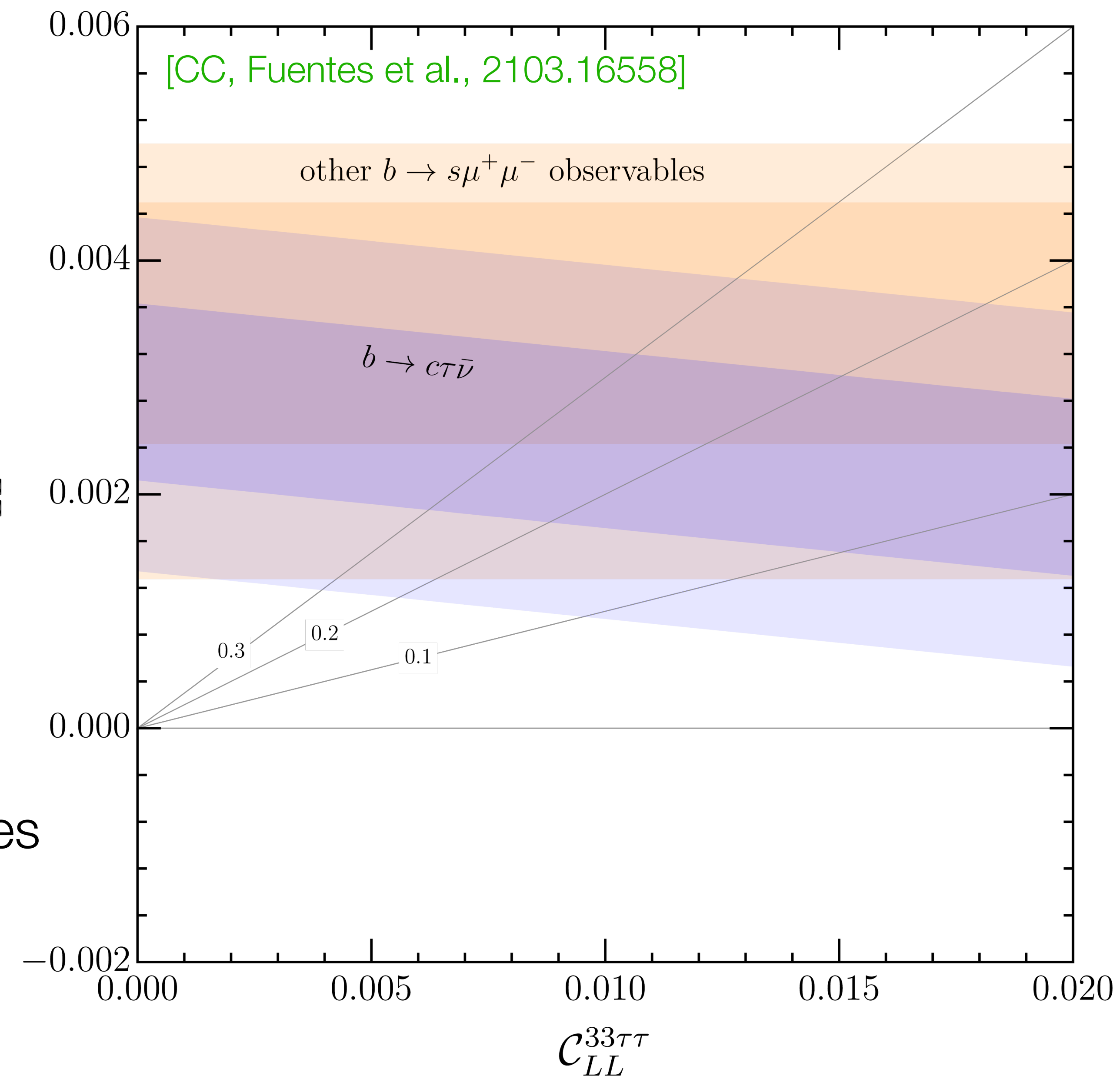
$b \to c$ $\quad b \to s$

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

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

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

- good consistency between the anomalies



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

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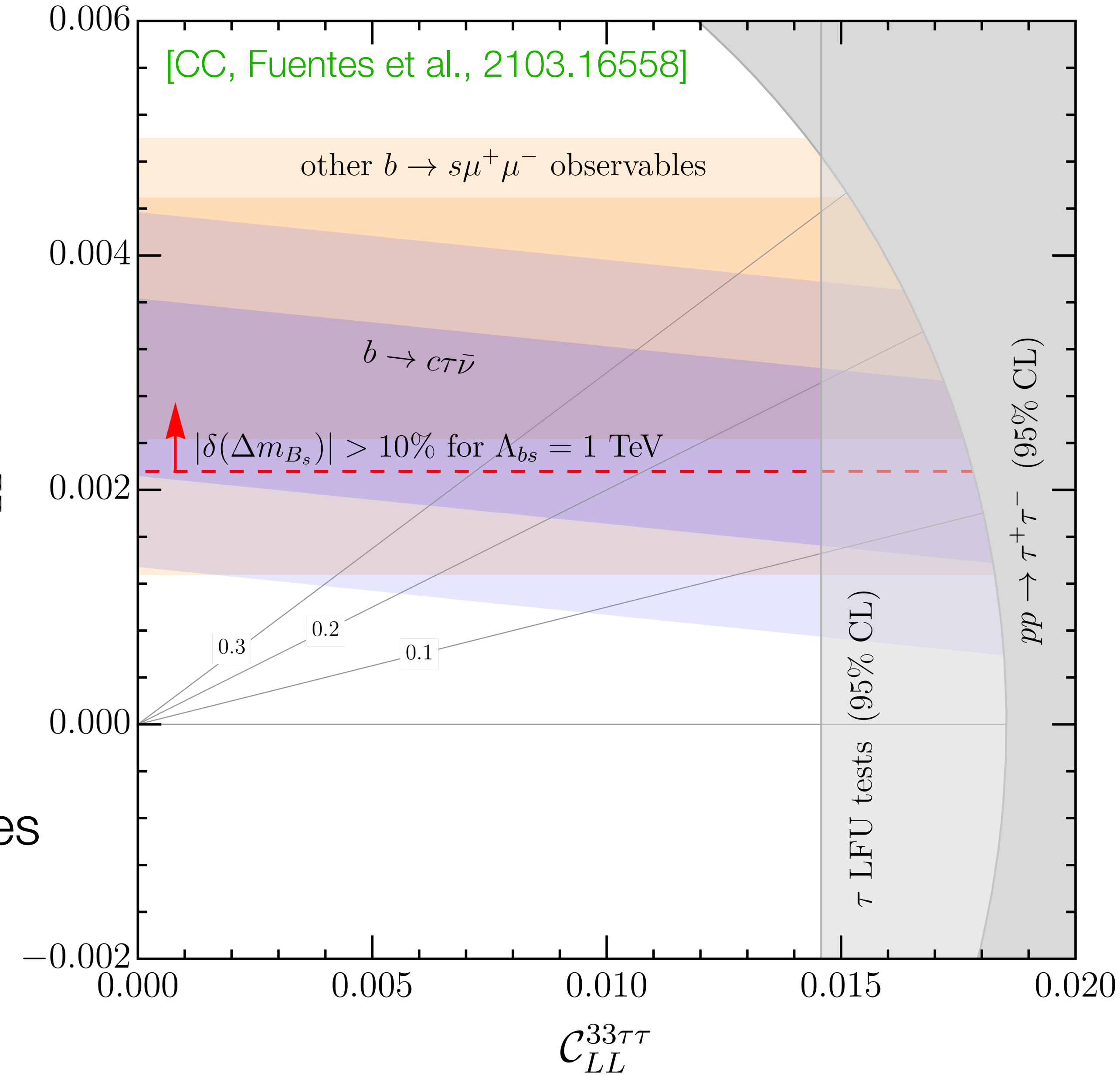
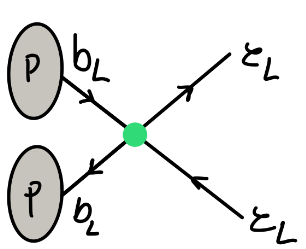
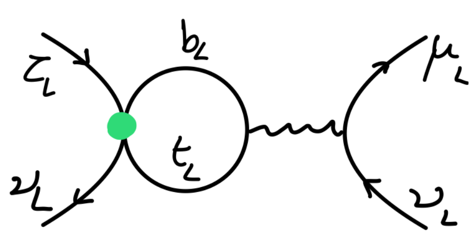


- good consistency between the anomalies

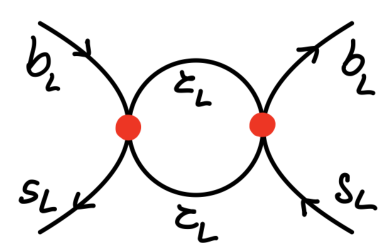
- but several constraints (driven by $R_{D^{(*)}}$)



$pp \to \tau\tau$



τ LFU tests



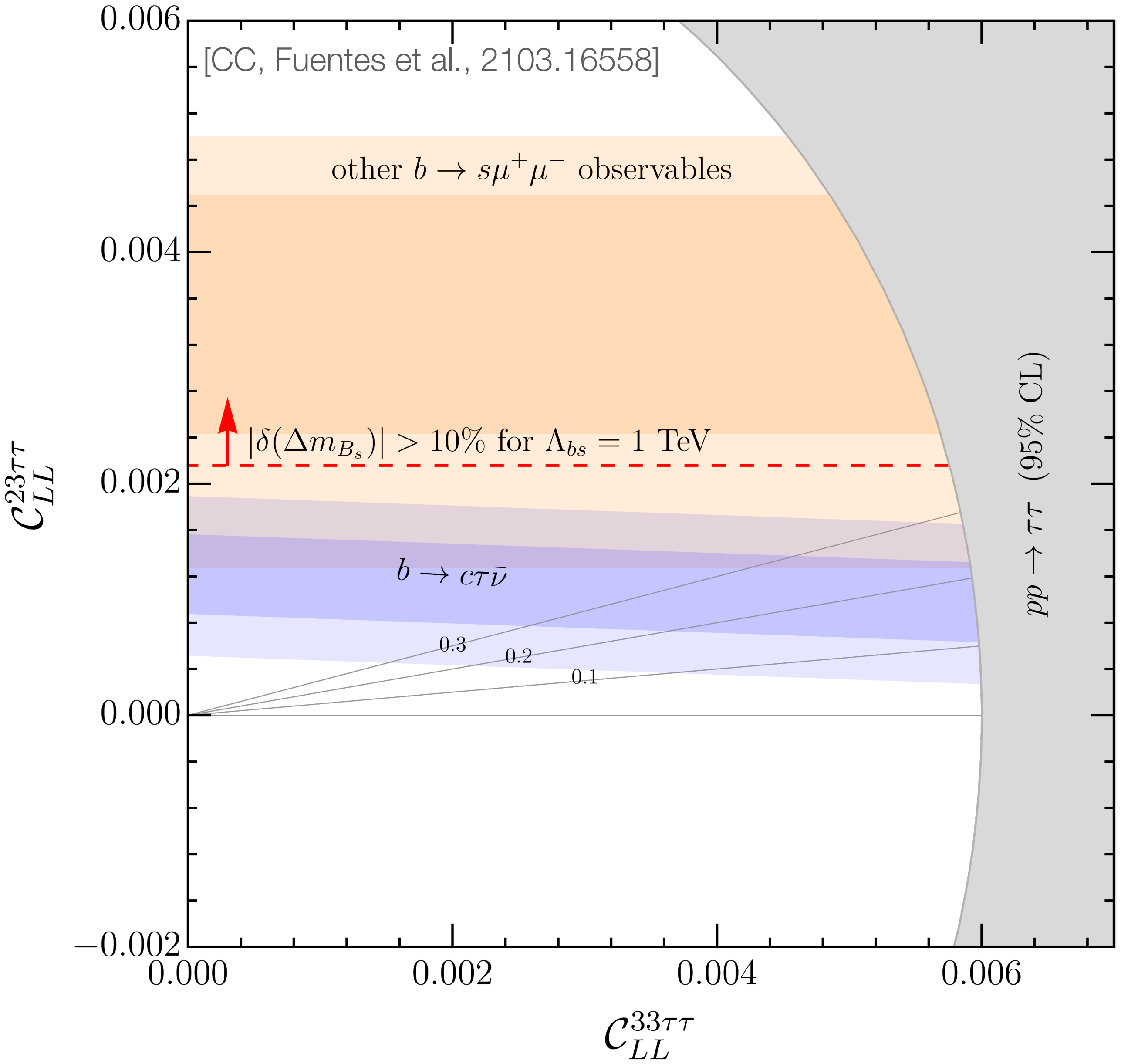
$B_s - \bar{B}_s$

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

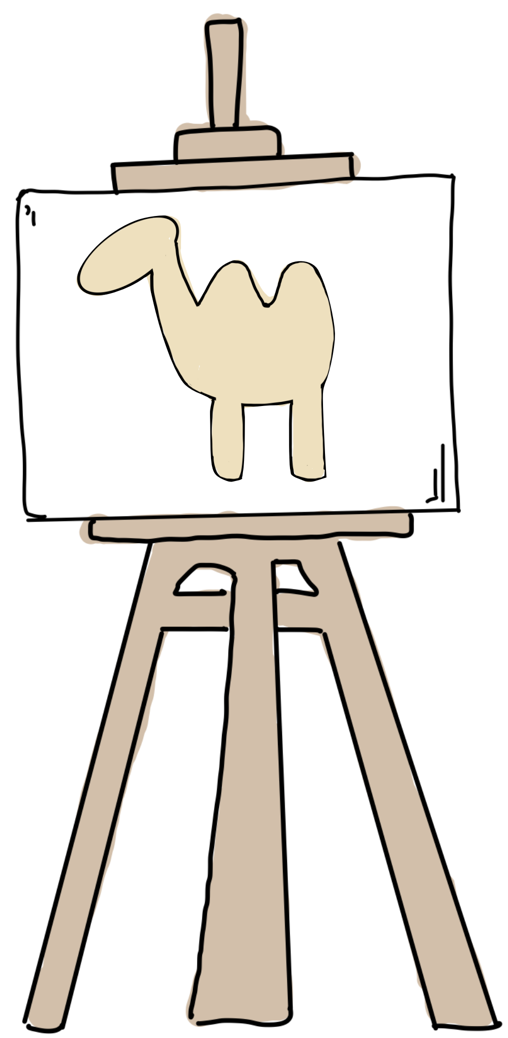
Possibile common origin L+R

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

- 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 can do both?

- Keeping these constraints in mind, only **leptoquarks** are viable tree-level mediators:
  - ✓ no 4-lepton and 4-quark processes at tree level
  - ✓ no resonant production in quark-quark initiated processes

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[Sumensari et al.. 2103.12504]

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 $(\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗	✗

- Finite number of possibilities:
  - $S_1 + S_3$ [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;
  - Three generations of S_2 [Crivellin, Schnell,Fuks 2203.10111] [Luc's talk on Wed.]

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All have pros and cons:

- Scalars are "simpler" in terms of matter content (standalone)
- Tricky to accommodate $b \to s\bar{\nu}\nu$ and/or $s \to d\bar{\nu}\nu$

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U_3	$(\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗	✗

- Finite number of possibilities:
  - $S_1 + S_3$ [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;
  - Three generations of S_2 [Crivellin, Schnell,Fuks 2203.10111] [Luc's talk on Wed.]

All have pros and cons:

- the vector leptoquark U_1 does not mediate $b \to s\nu\bar{\nu}$, $s \to d\bar{\nu}\nu$ at tree level
- needs a UV completion (additional heavy vectors + fermions)
- points to quark-lepton unification, can realize an $U(2)^5$ from non-universal gauge symmetry

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]

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

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

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

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

Two interesting benchmarks: 1. $\beta^R_{b\tau} = 0$ (no RH currents)

2. $|\beta^R_{b\tau}| = |\beta^L_{b\tau}| = 1$ (max RH currents)

[models with 3rd family quark-lepton unification]

Both give a good description of all low-energy data, with a U(2)-like flavor structure.

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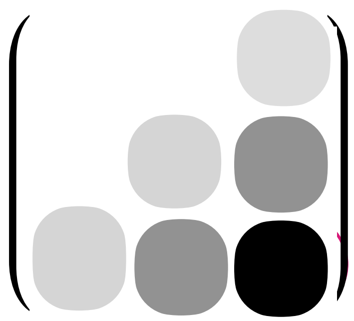
$\beta^L =$ 

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

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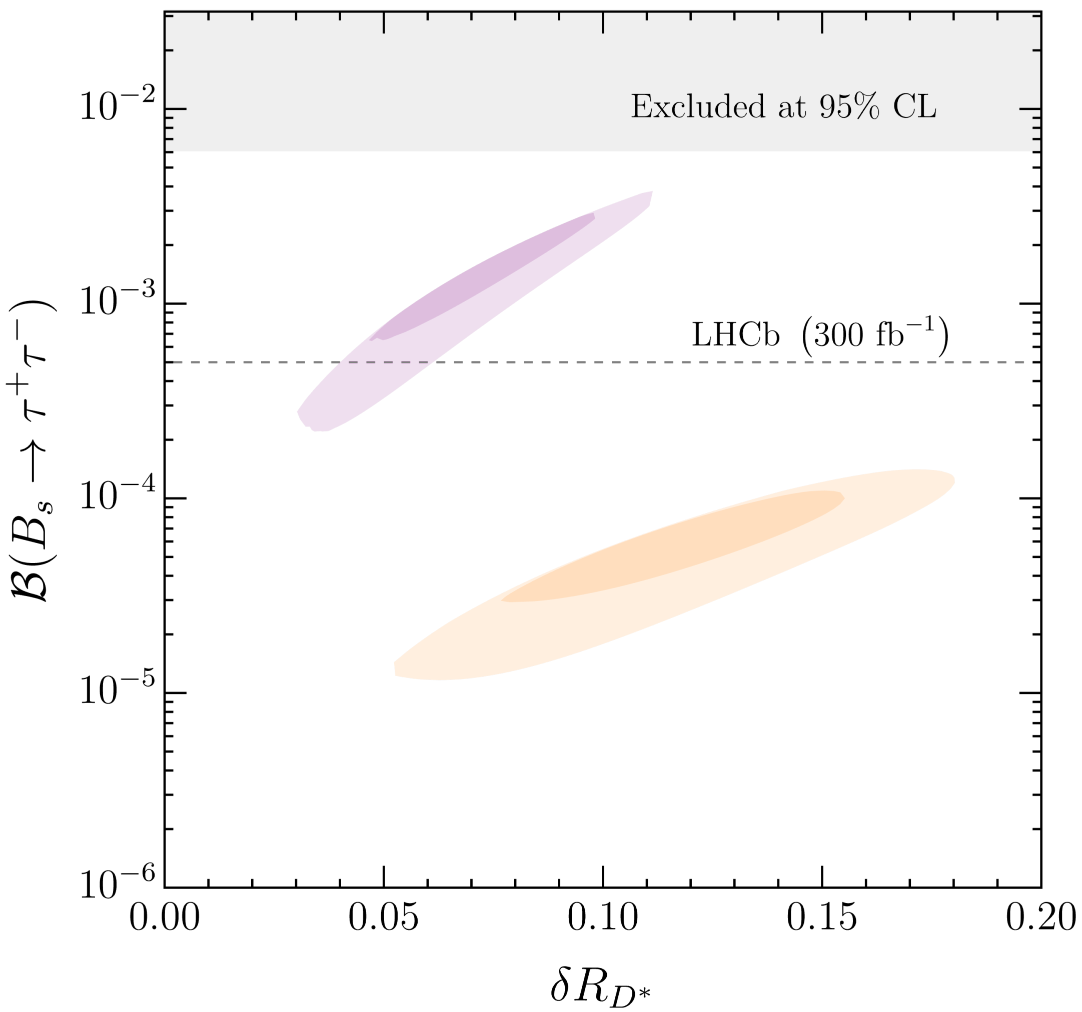
The U_1 simplified model: low-energy

Rich phenomenology at low & high energy:

- **large $b \to s\tau\tau$ (driven by $R_{D^{(*)}}$)**



no RH currents

$$\frac{\mathcal{B}(B_s \to \tau\tau)}{\mathcal{B}(B_s \to \tau\tau)_{\rm SM}} \approx \frac{\mathcal{B}(B \to K\tau\tau)}{\mathcal{B}(B \to K\tau\tau)_{\rm SM}} \approx 1 \times 10^2$$

with RH currents

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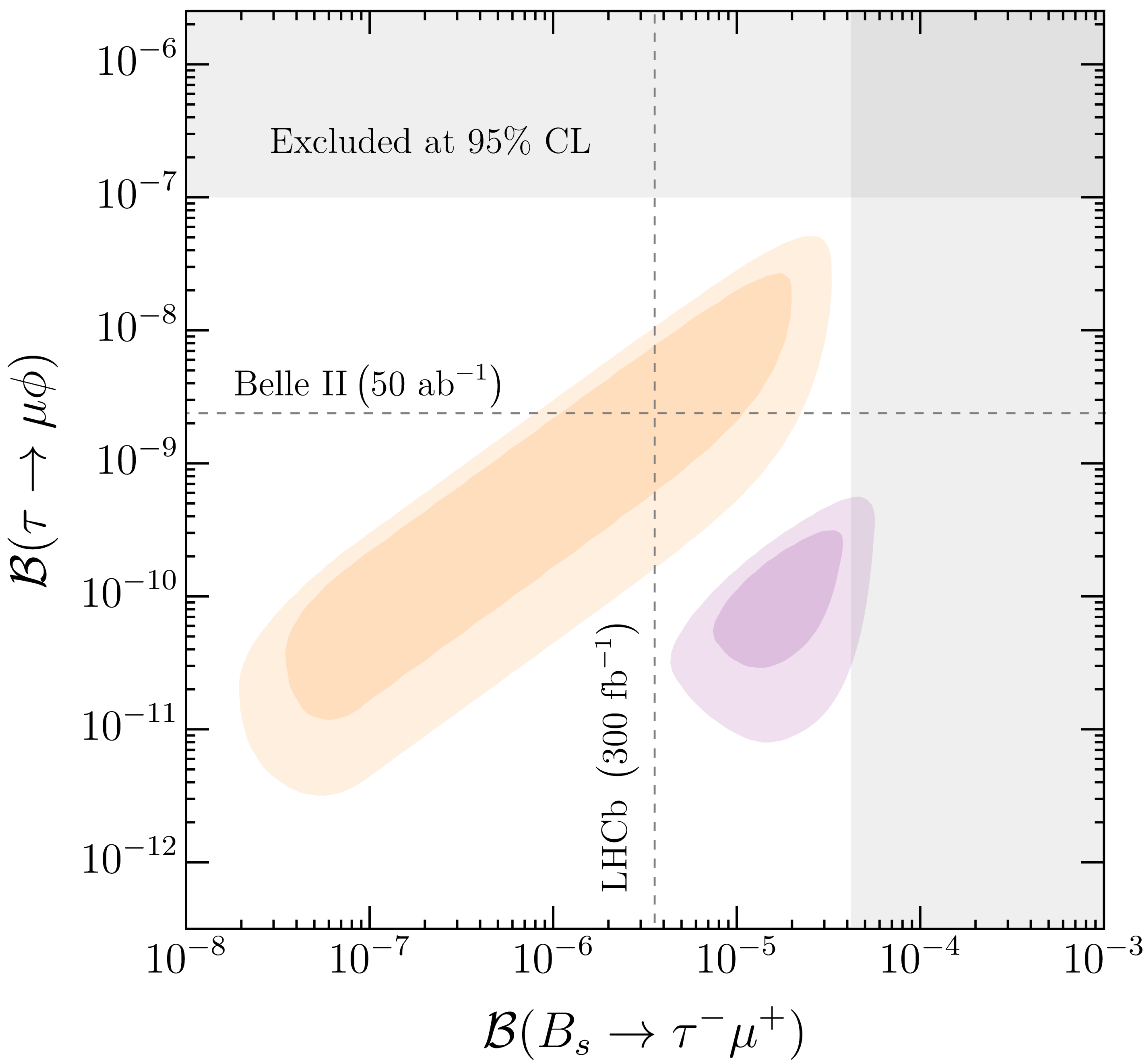
The U_1 simplified model: low-energy

Rich phenomenology at low & high energy:

- **large τ/μ LFV in $b \to s\tau\mu$ and τ decays**
  (driven by simultaneous presence of $R_{D^{(*)}}$ & $R_{K^{(*)}}$)



[CC, Fuentes-Martin et al., 2103.16558]

no RH currents

$$\mathcal{B}(B_s \to \tau\mu) \approx \mathcal{B}(B \to K\tau\mu) \approx 10^{-7} - 10^{-6}$$

$$\mathcal{B}(\tau \to \mu\phi) \approx 10^{-10} - 10^{-8}$$

with RH currents

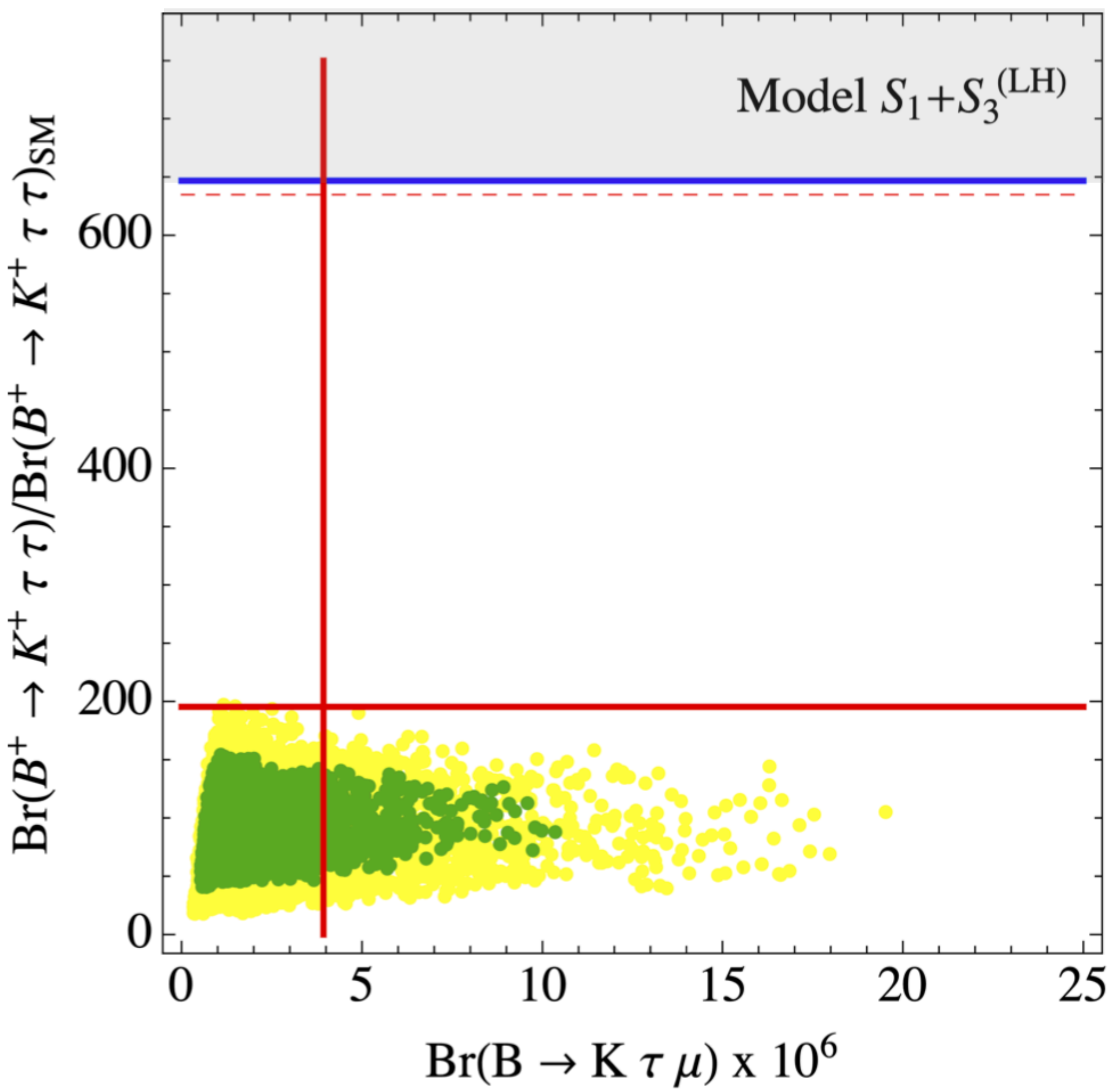
$$\mathcal{B}(B_s \to \tau\mu) \approx 1 \times 10^{-5}$$

$$\mathcal{B}(B \to K\tau\mu) \approx 1 \times 10^{-6}$$

$$\mathcal{B}(\tau \to \mu\gamma) \approx 1 \times 10^{-8}$$

The $S_1 + S_3$ simplified model: low-energy

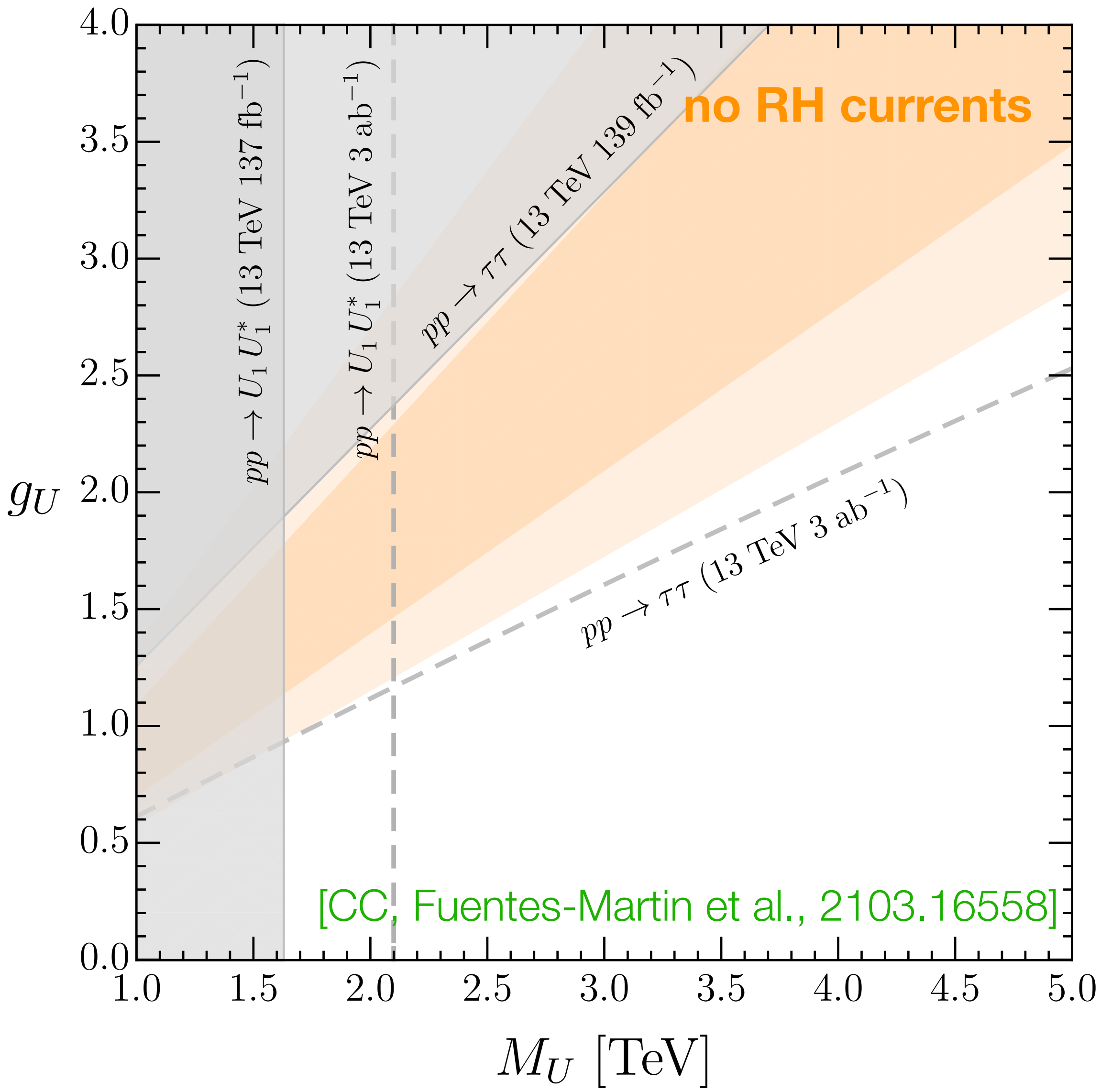
Similar signatures for the other simplified models, e.g. $S_1 + S_3$



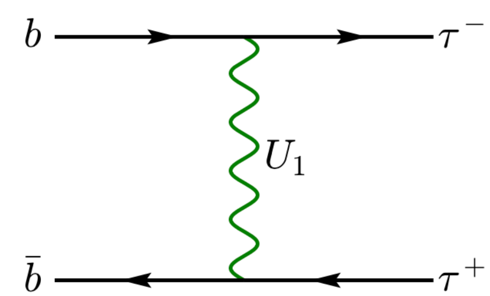
[Gherardi, Marzocca, Venturini 2008.09548]

The U_1 simplified model: high - pT

- The same interaction can be probed at high energy:



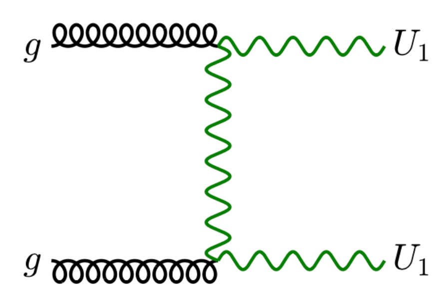
- $pp \to \tau\tau$ **tails**
  (Drell-Yan t-channel exchange)



(Recast) ATLAS EXPERIMENT

2002.12223

- $pp \to U_1^* U_1 \to b\tau t\nu$



$U_1 \to b\tau^+, t\bar{\nu}$

$\mathscr{B}(U_1 \to b\tau^+) \approx 0.5$

CMS

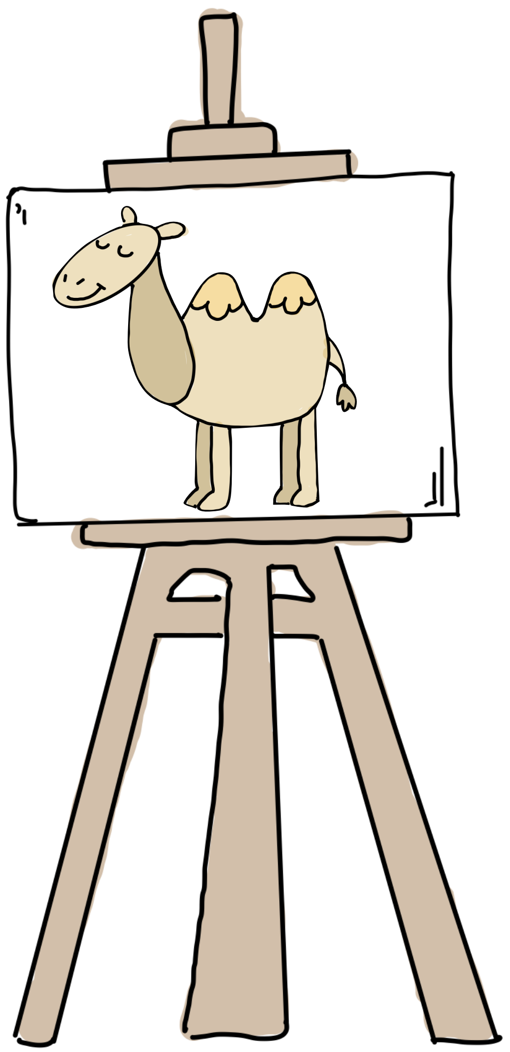
2012.04178

$\longrightarrow$ HL-LHC will fully probe the vector LQ solution

(same for $R_2 + S_3$, still space left for $S_1 + S_3$)

- Similar enhancements in all models for $R_D^{(*)}$ (drives all these “big” signatures…)

NP interpretation (III): UV completing the U_1



UV-completing the U_1: the gauge path

- UV completions of the U_1 point to variations of the **Pati-Salam** group.

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

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

$$SU(4) \sim \left(\begin{array}{c:c} G^a & U^\alpha \\ \hdashline (U^\alpha)^* & Z' \end{array}\right) \qquad \psi_{L,R} = \begin{bmatrix} q^\alpha_{L,R} \\ q^\beta_{L,R} \\ q^\gamma_{L,R} \\ l^\delta_{L,R} \end{bmatrix} \qquad \mathrm{PS/SM} \ni U_1, Z'$$

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- The original PS does not work:
need additional $SU(3)$ to decorrelate $SU(4)$ from $SU(3)_c \Longrightarrow$ **4321** models

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

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

$$4321/\mathrm{SM} \ni U_1, Z', G' \sim (8,1,0)$$

Non-universality in 4321

How to make the U1 interactions with SM fermions non-universal?

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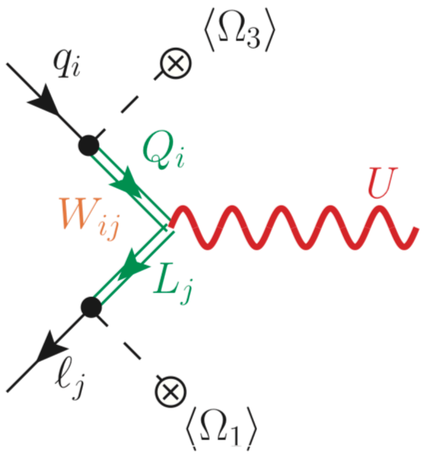

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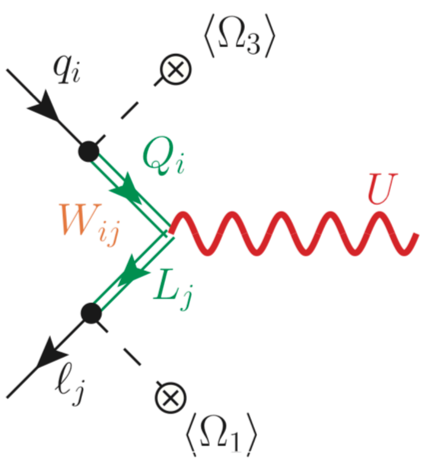

Depending on the charges of the VLF, the U1 couple to LH and/or RH SM fields.

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

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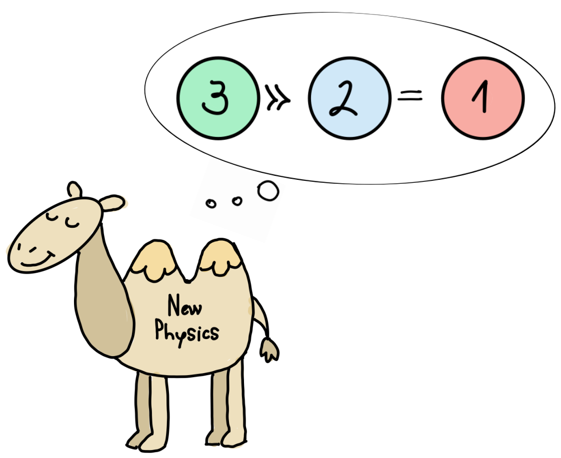

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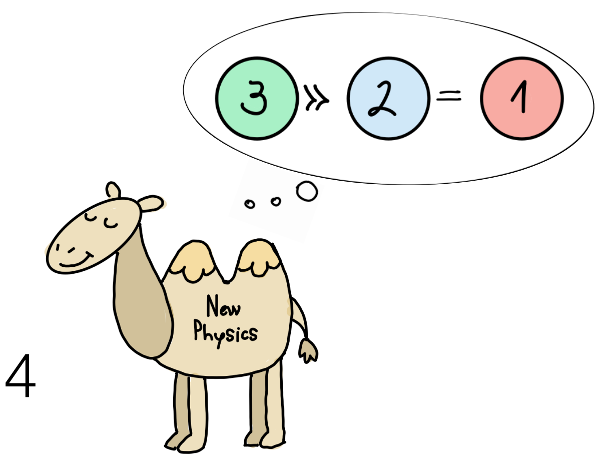

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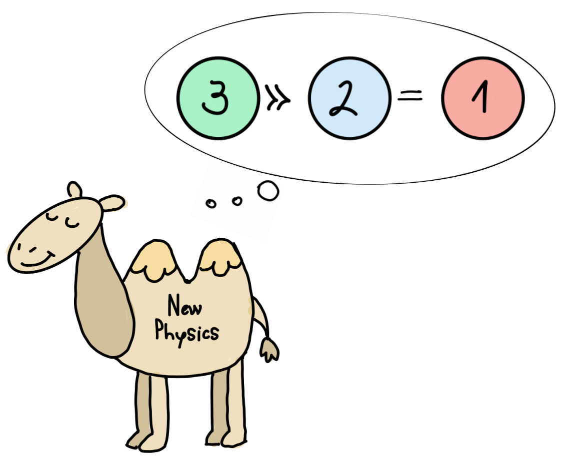

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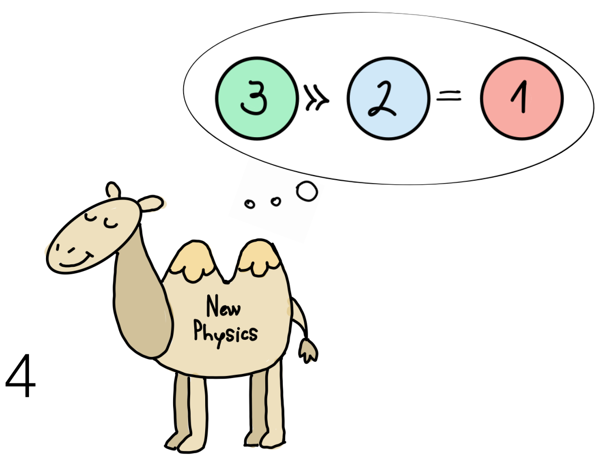

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$\Rightarrow$ nice connection between flavor anomalies & hierarchies!

Importance of loop effects

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

- $B \to K\nu\bar{\nu}$ 20-50% enhancement over the SM, in the reach of Belle II [talk by Sally]

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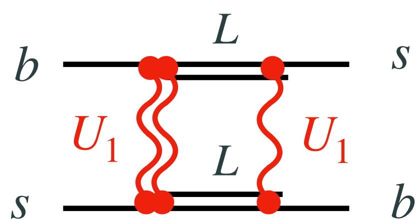
- B_s-$\bar{B}_s$ **mixing**



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

$U(2)_q$ breaking, fixed by $R_{D^{(*)}}$

VL lepton mass

With the current $R_{D^{(*)}}$, need $M_L \lesssim 1.5\ \mathrm{TeV}$ not to overshoot Δm_{B_s}

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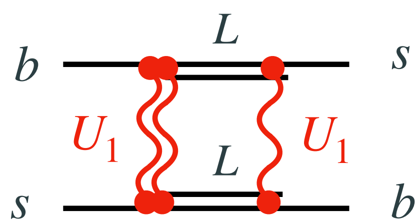

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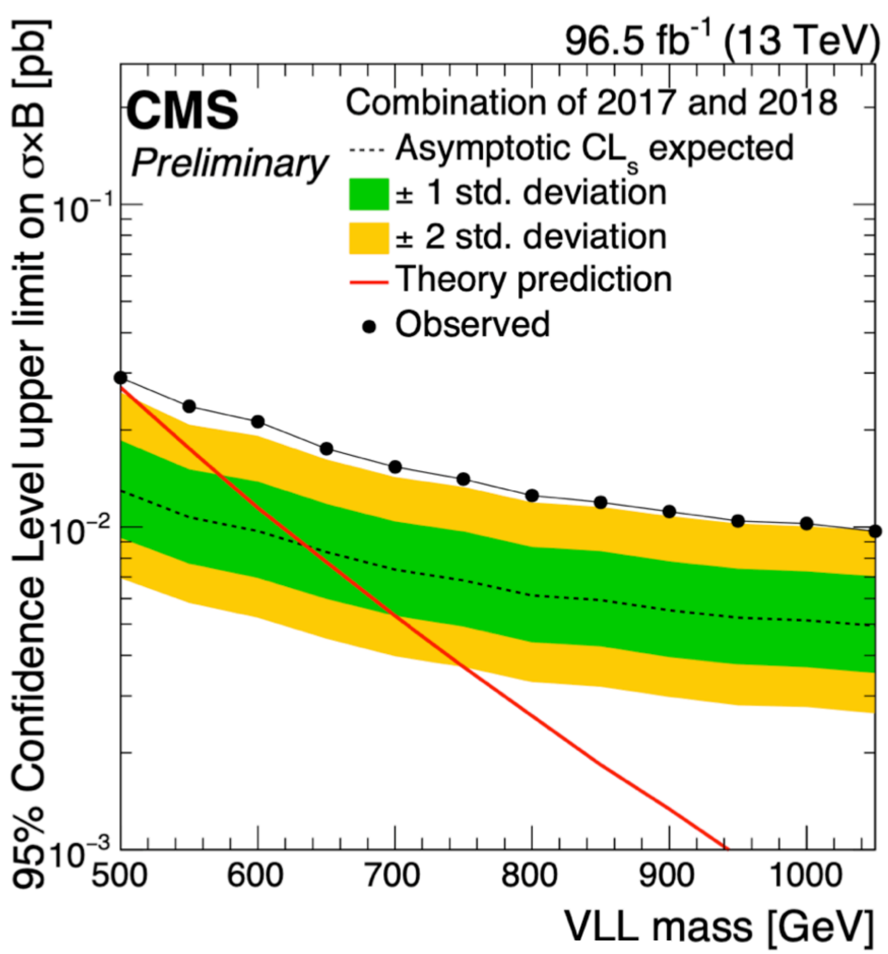
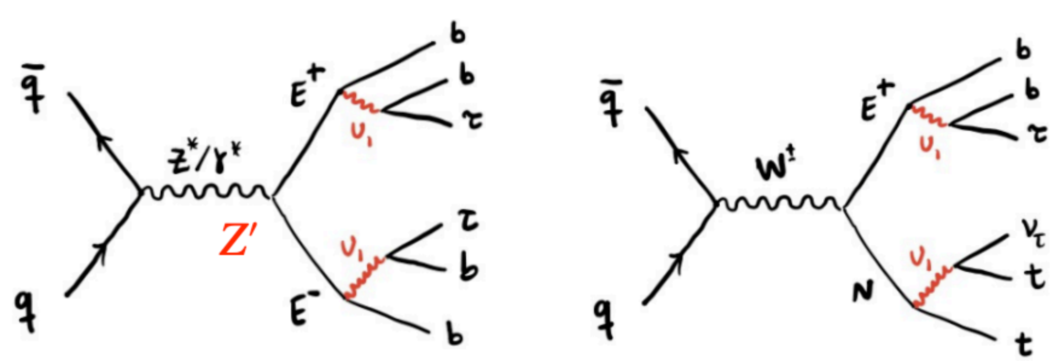


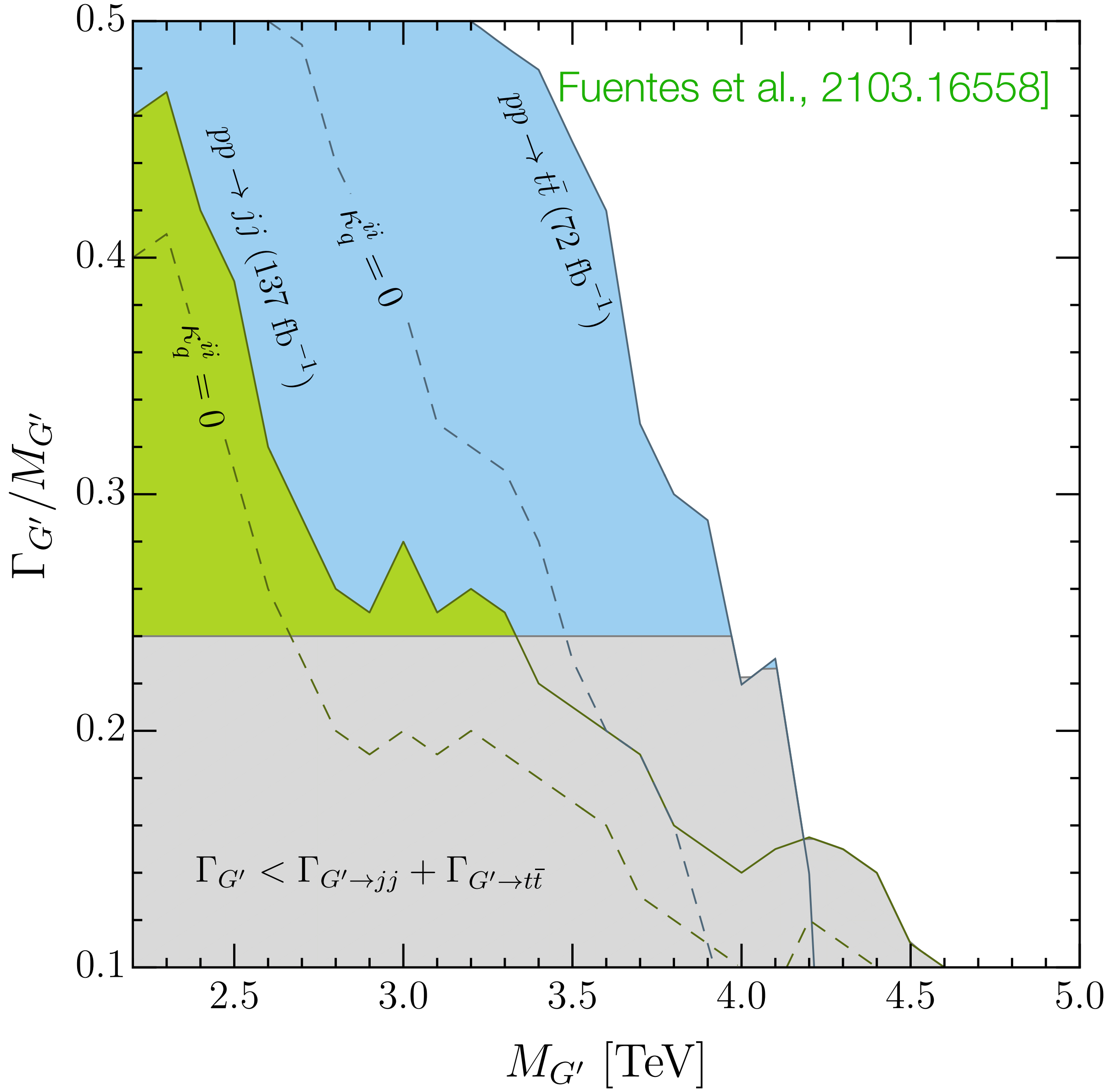
[CMS Public result: B2G-21_004]

CMS search for 4321 VL leptons:
$2.8\,\sigma$ preference for VL lepton with $m \approx 600$ GeV

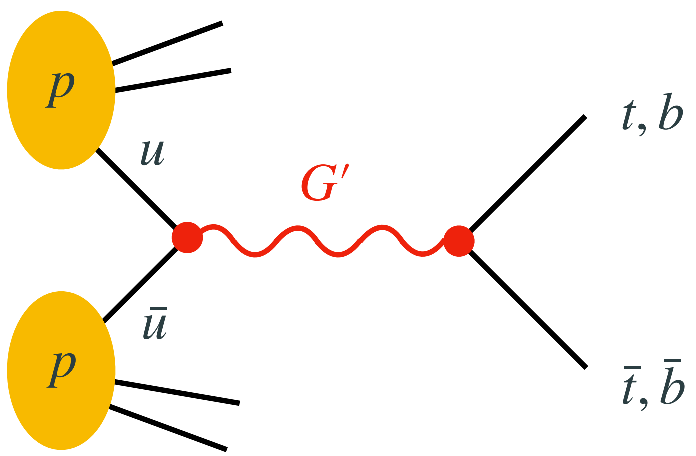


[Kormier,Faroughy, Fuentes, Mikuni w.i.p.]

Coloron direct searches at the LHC



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



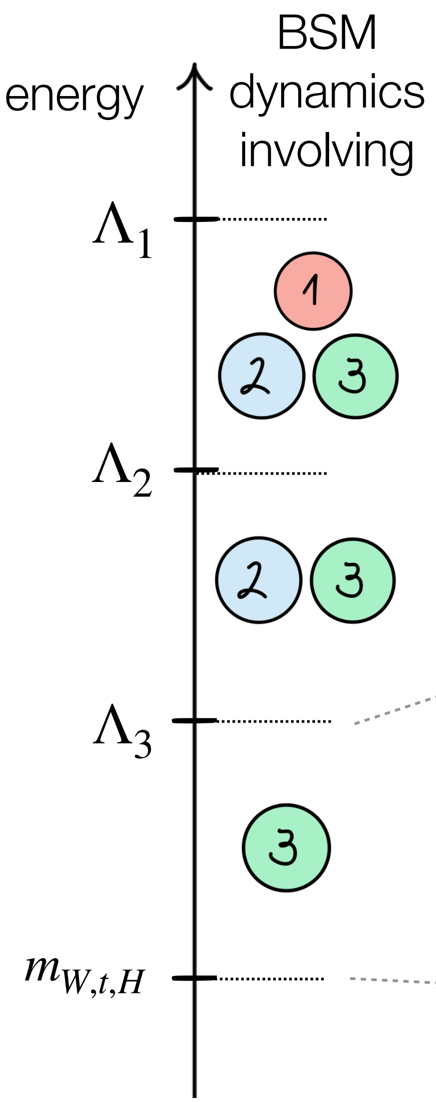
→ G'-mediated $pp \to tt$ gives the strongest constraint on the overall scale of the model!

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

Even more UV complete: 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:

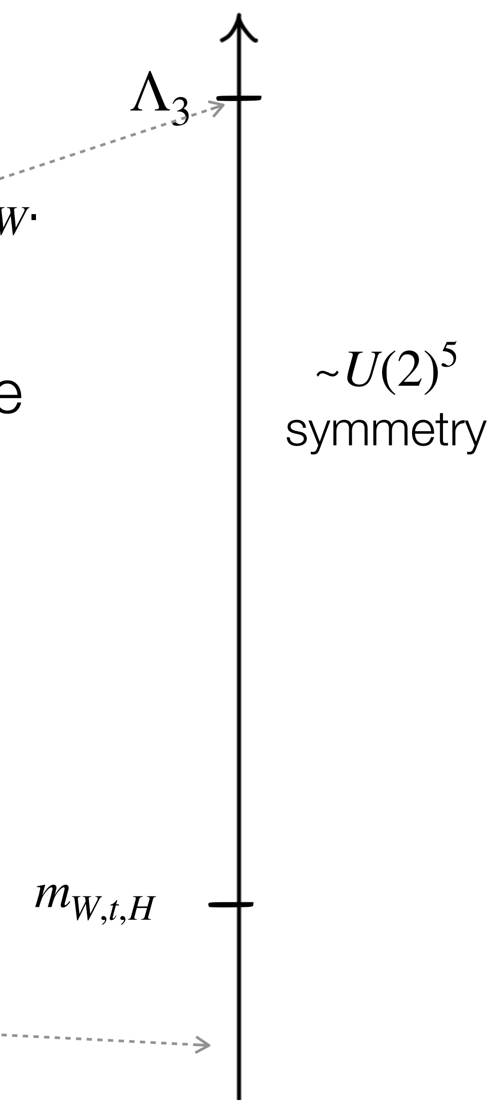


New, non-universal interactions (for us: gauge) acting on the i-th SM family switch on at $\Lambda_1 \gg \Lambda_2 \gg \Lambda_3 \gg m_W$.

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

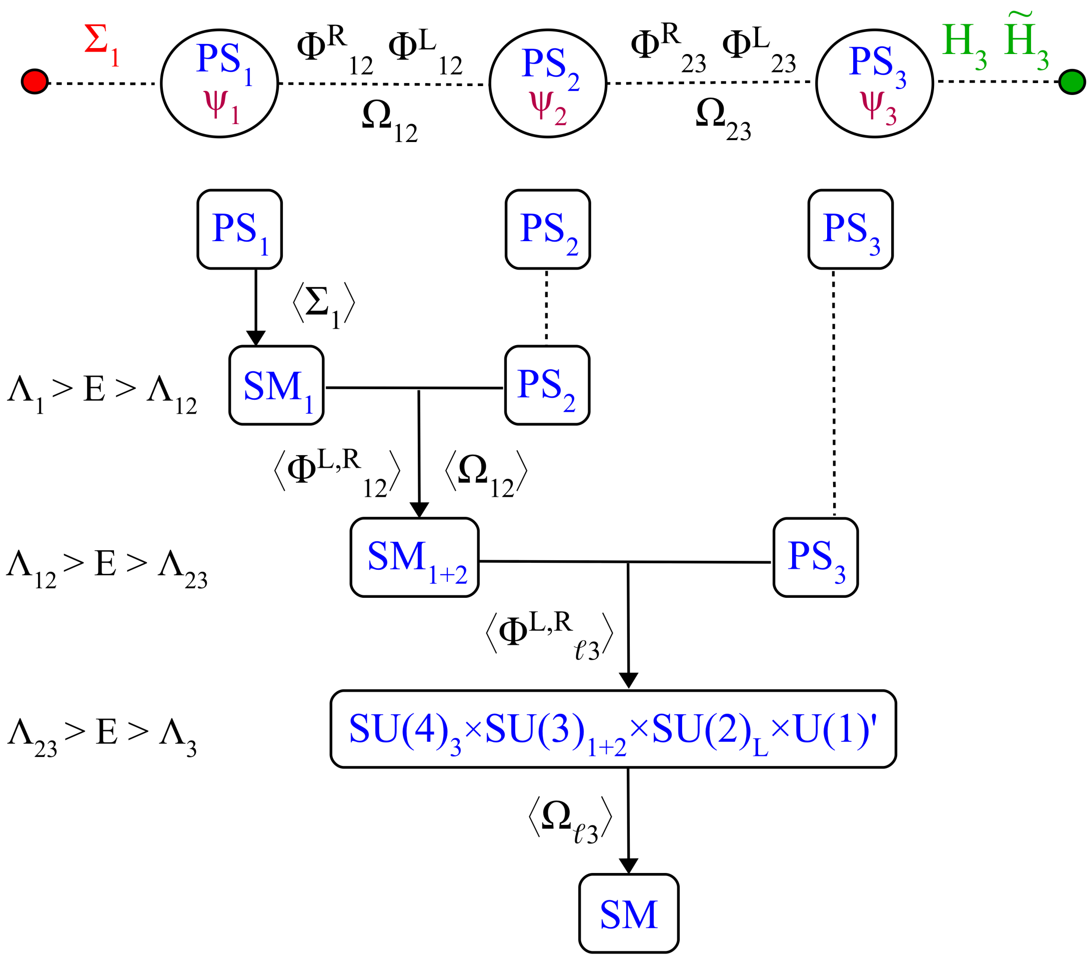
New Physics is flavor non-universal; universality is a low-energy accident.

Λ_3 can be as low as few TeV.



Non-universal Pati-Salam unification

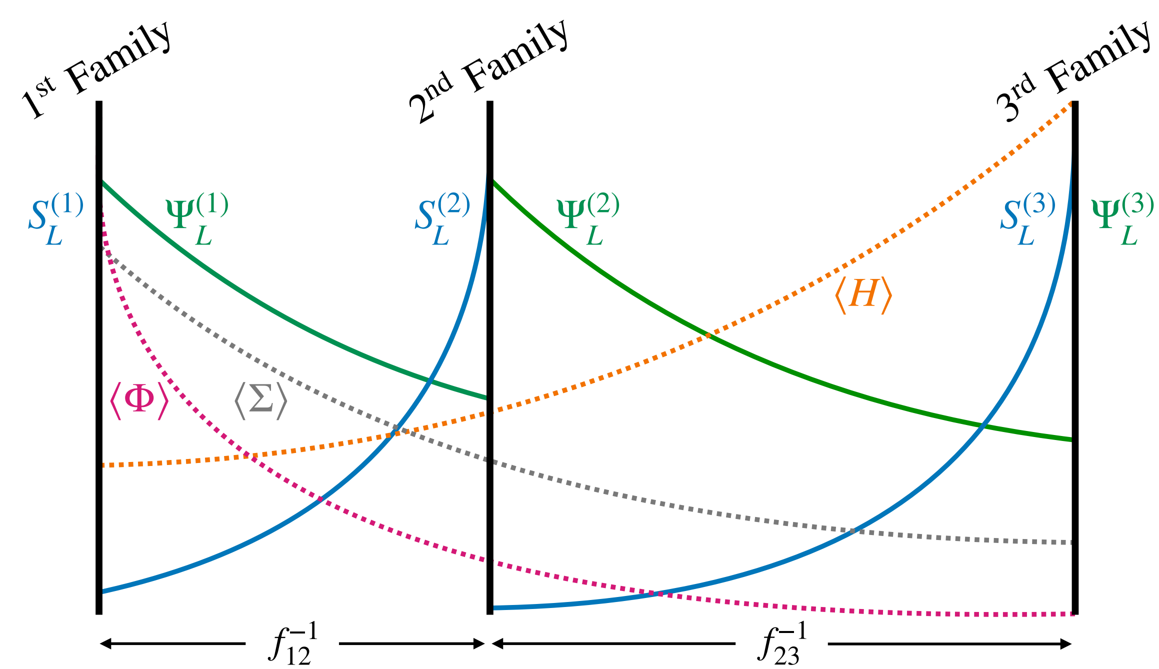
- **PS^3: 4D three-site model**



[Bordone, CC, Fuentes, Isidori 1712.01368]

- **5D construction** [talk by Ben tomorrow]

warped compact extra dimension with multiple 4-dimensional branes



[Fuentes-Martin, Isidori, Pagès, Stefanek, 2012.10492]

[Fuentes-Martin, Isidori, Lizana, Stefanek, Selimovic, 2203.01952]

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 & Anders Ellen Thomsen's talk @Panic 2021]

NP in $(g-2)_\mu$: considerations about the scale

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

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

To explain it, need NP light ($\ll v_{\text{EW}}$) & weakly coupled or heavy & “strongly” coupled.

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No light candidate in 4321 $\rightarrow$ stick to heavy option.

NP in $(g-2)_\mu$: considerations about the scale

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

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How heavy?

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

$g_{\rm NP} \sim 1$ and no chiral enhancement w.r.t SM $\Rightarrow M_{\rm NP} \sim v_{\rm EW}$

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

with chiral enhancement (e.g $m_f = m_t$) $\Rightarrow M_{\rm NP} \sim 1 - \mathcal{O}(10)$ TeV

NP in $(g-2)_\mu$: considerations about the flavor structure

To address the (g-2) and be consistent with cLFV bounds, NP models need to fulfil strong flavor alignment conditions in the lepton sector.

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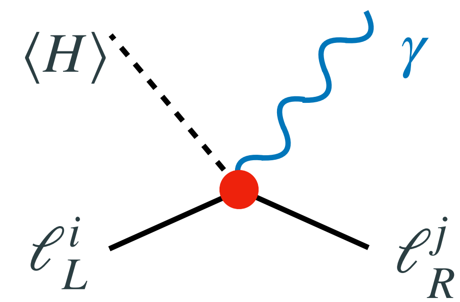

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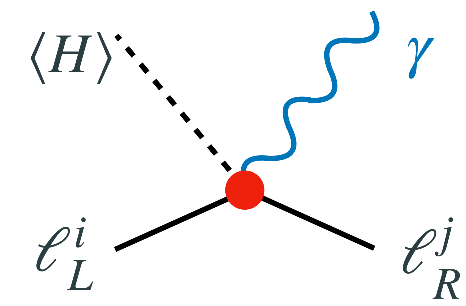

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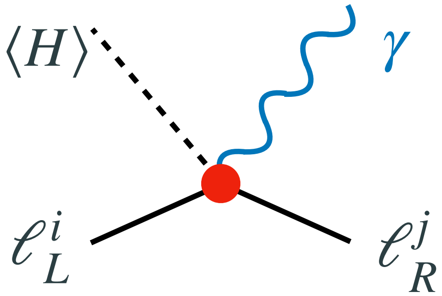

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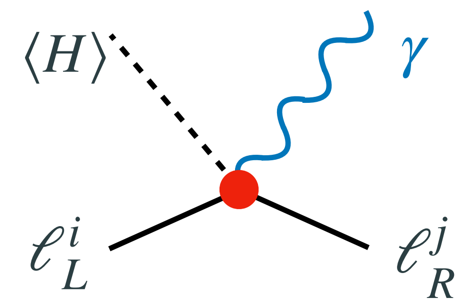

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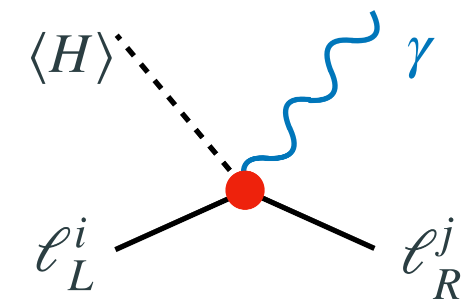

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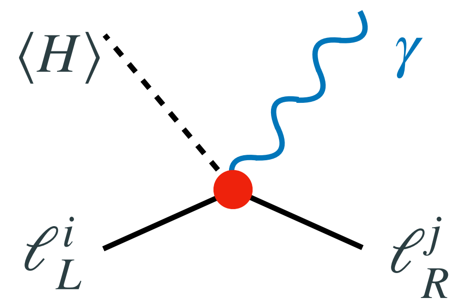

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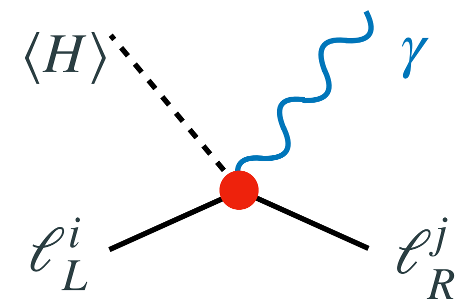

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$\Longrightarrow$ Not easy to reconcile $(g-2)_\mu$ with both B anomalies.

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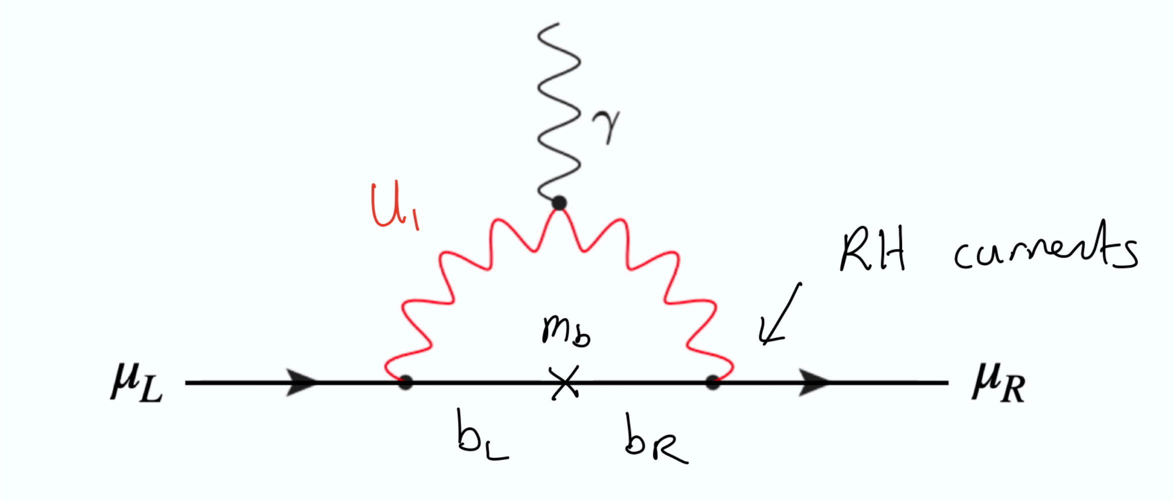

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$$\sim 10^{-9}\left(\frac{3\ \mathrm{TeV}}{m_{\mathrm{LQ}}}\right)^2\left(\frac{s_{\mu_L}}{0.2}\right)\left(\frac{s_{\mu_R}}{0.2}\right)$$

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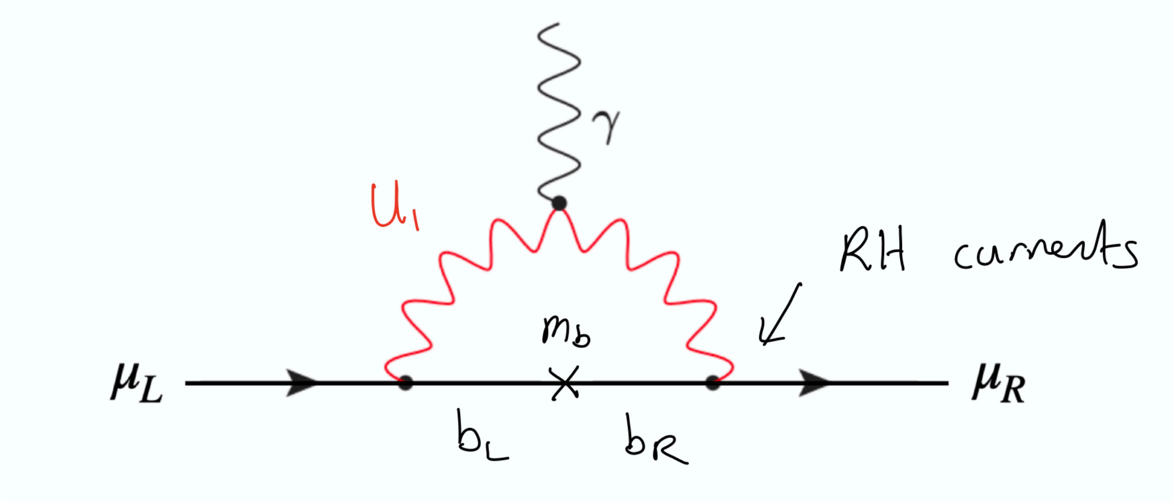

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But RH currents generate the scalar operator $\mathcal{O}_s \sim \frac{m_b}{m_\mu} V_{ts}\left(\bar{s}_L b_R\right)\left(\bar{\mu}_R \mu_L\right)$

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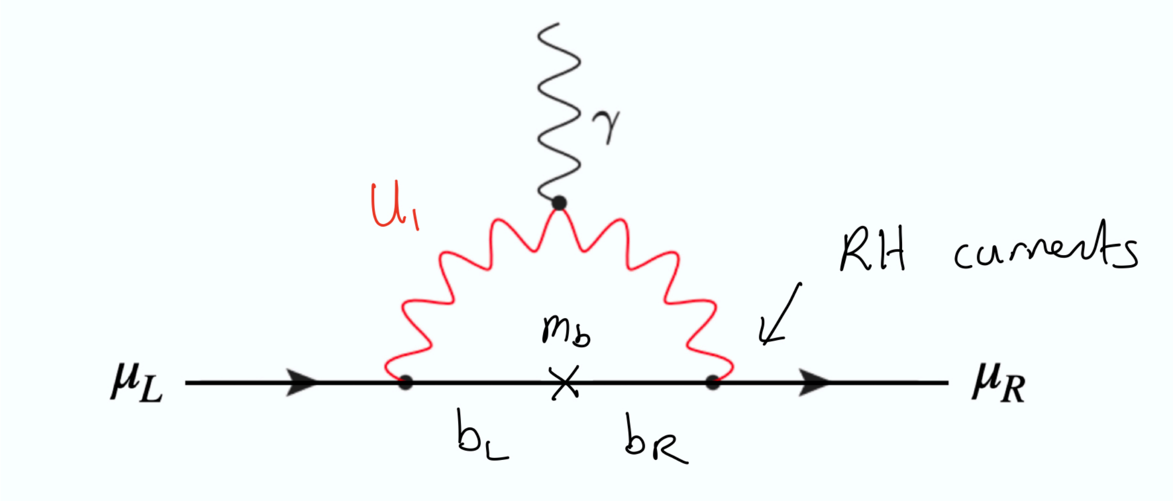

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⇒ 4321 as it is does not work. Need something else.

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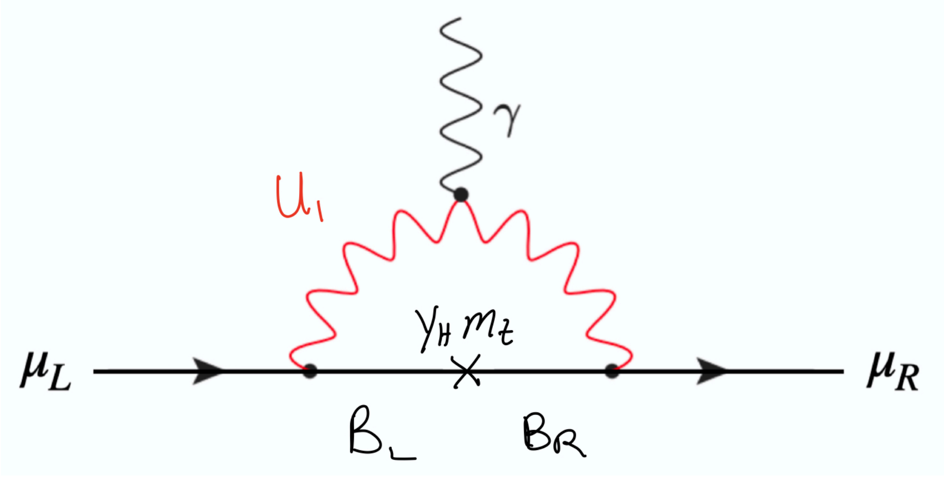

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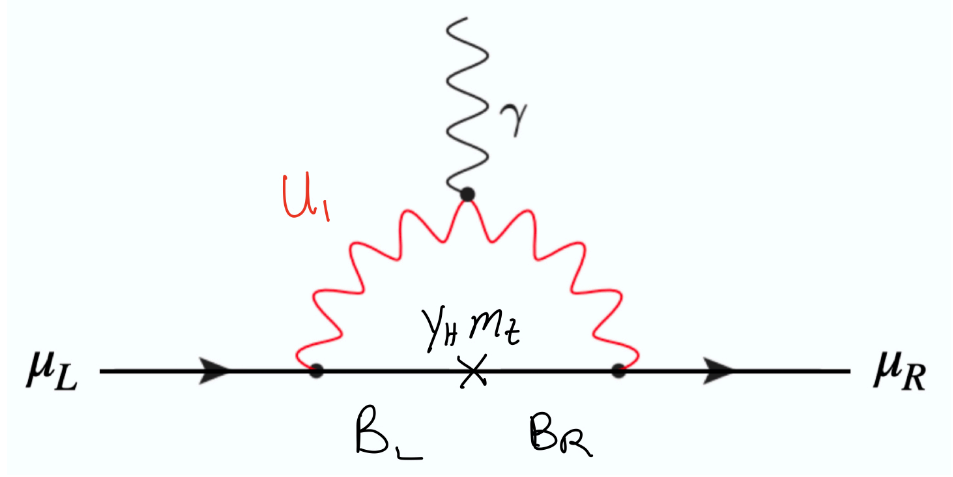

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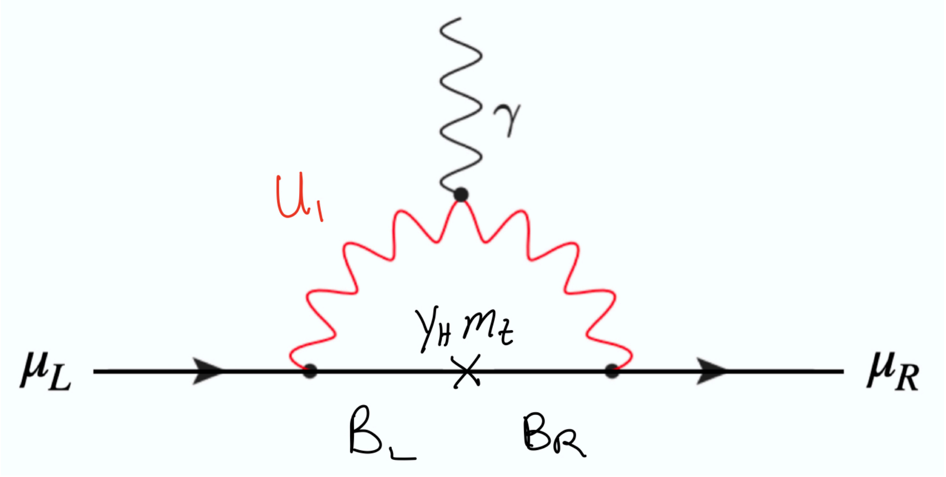

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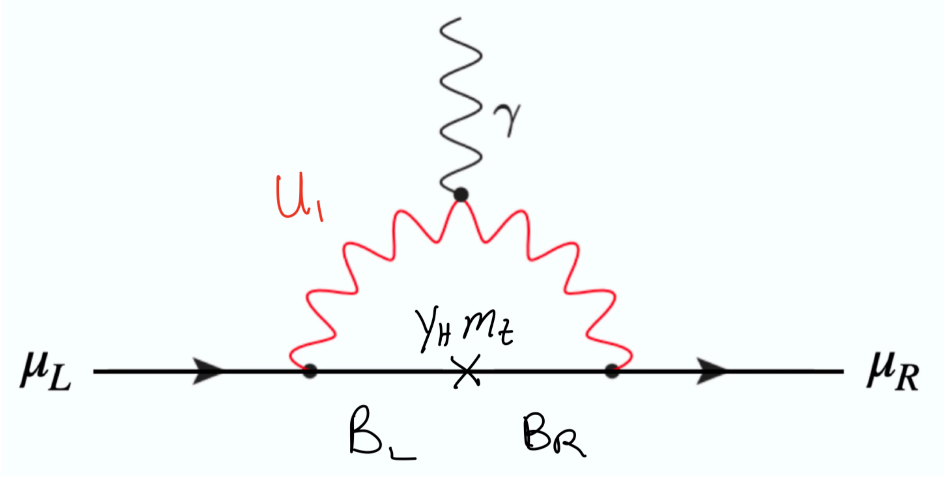

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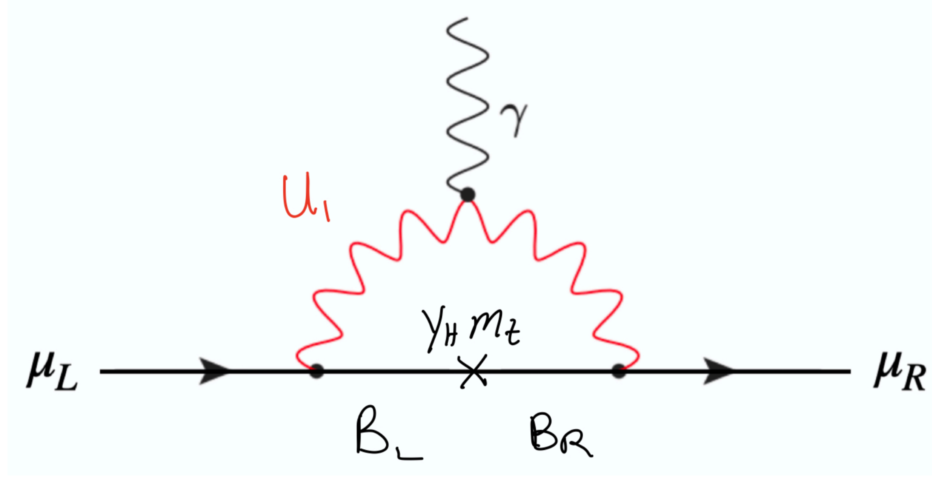

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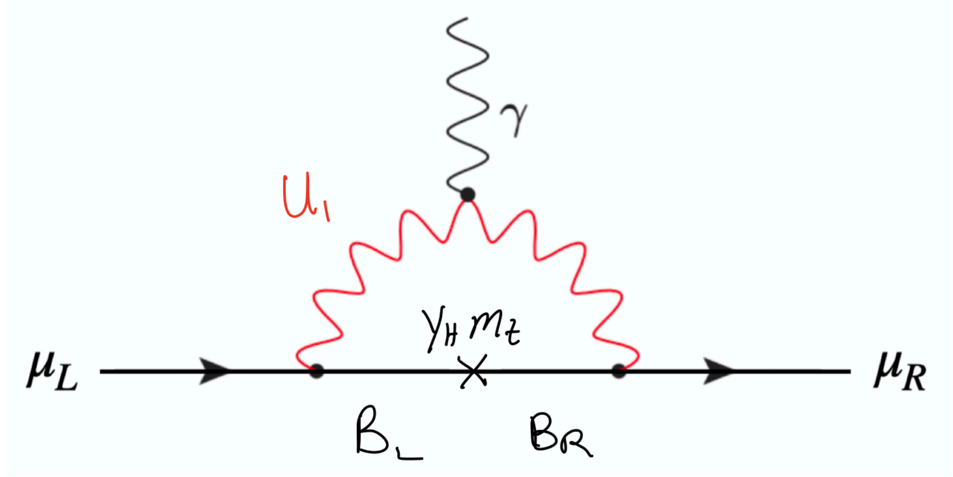

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$\Longrightarrow$ again, need something else.

A possible solution within universal 4321

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

A better idea is to enlarge the **scalar sector**: double the scalars breaking 4321 ($\boldsymbol{\Omega}_i$) and add a Z_2 symmetry softly broken by the scalar potential.

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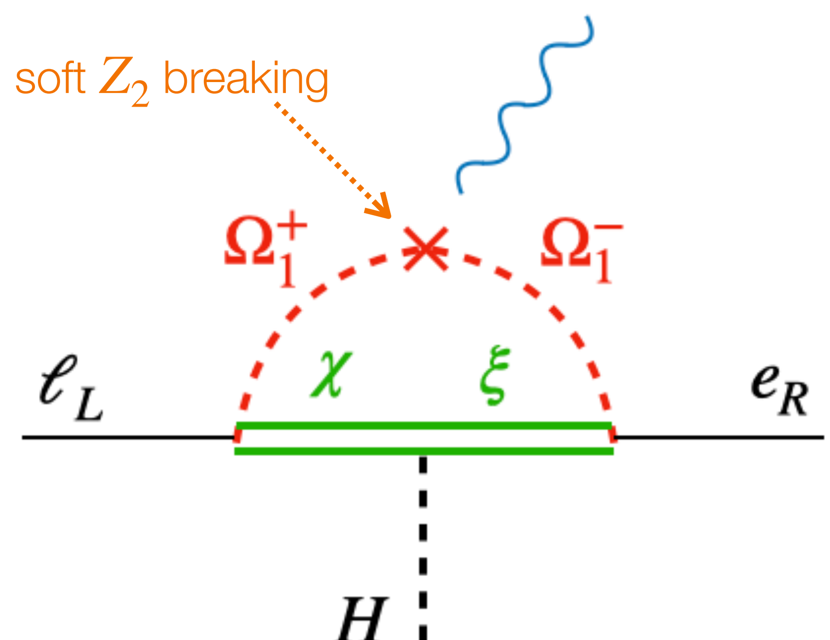
Ω_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$	0	$+$	$\mathbf{1}$

$(g-2)_\mu$ via scalar loop, enhanced by hierarchical choice of the vevs for scalars of opposite parity (~ 2HDM with large $\tan\beta$).



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

A possible solution within universal 4321

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

A better idea is to enlarge the scalar sector: double the scalars breaking 4321 ($\boldsymbol{\Omega}_i$) and add a Z_2 symmetry softly broken by the scalar potential.

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	$+$	$\mathbf{1}$

Z_2 forbids potentially dangerous tree-level Yukawas for charged leptons; $\delta y_\mu^{\text{mix}}$ is suppressed if $\tan\beta_1 \gg 1$.

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

forbidden by Z_2

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

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$\Rightarrow$ Explaining $(g-2)_\mu$, $b \to sll$ and $b \to c\tau\nu$ in 4321 is possible, but with additional ingredients. This boils down to the different flavor structures these obs. hint at.

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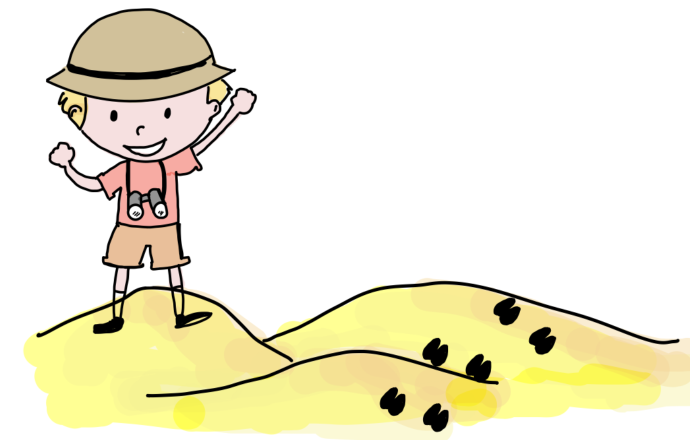
"Easier" to think of models for $(g-2)_\mu$ and $b \to sll$ only

E.g. "Muonic forces"

[Greljo, Stangl,Thomsen, 2103.13991, Greljo, Soreq, Stangl,Thomsen, Zupan; 2107.07518]

[see Anders' talk last week]

Conclusions



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.

- 4321 models are an interesting direction
  - → 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.