

B-physics Anomalies: from Data to New Physics Models

Claudia Cornella

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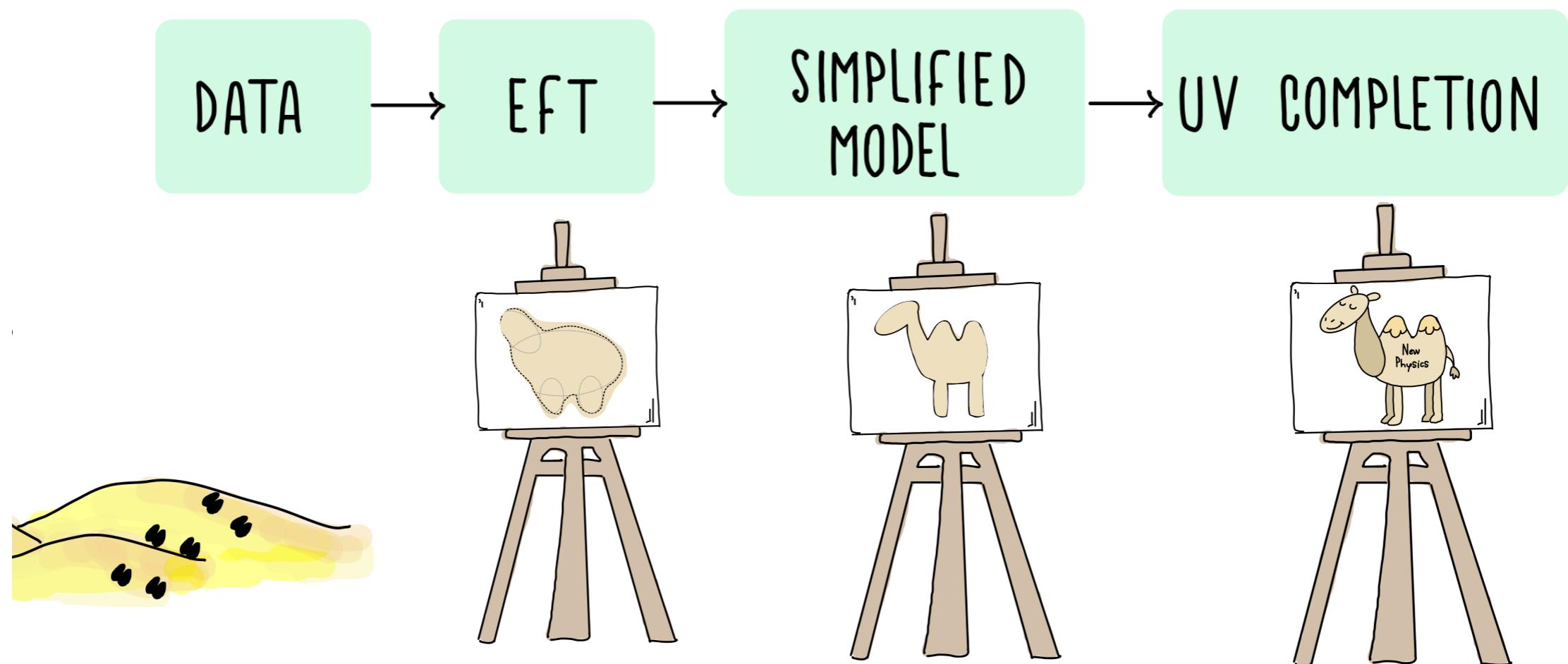
Reading the footprints of the B anomalies

- ? If the B anomalies are true NP signals, which NP could be responsible for them?
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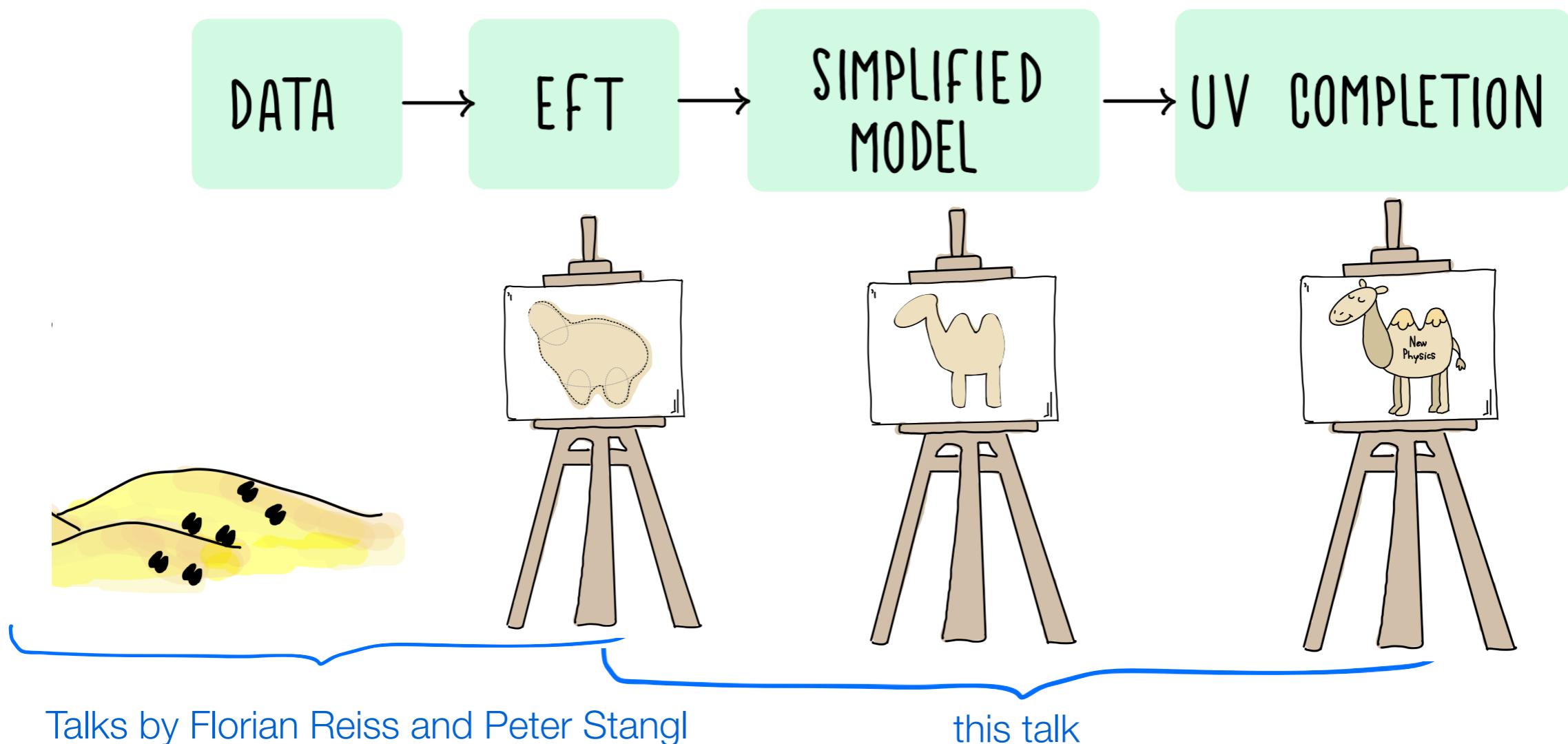
Usual strategy:



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Usual strategy:



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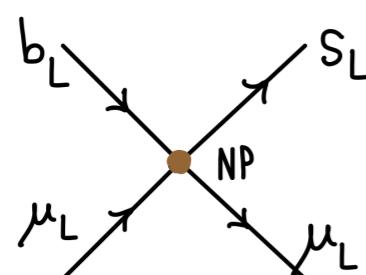
- New Physics in C_9^μ only, or
- **Left-handed NP** $\Delta C_9^\mu = -\Delta C_{10}^\mu$

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

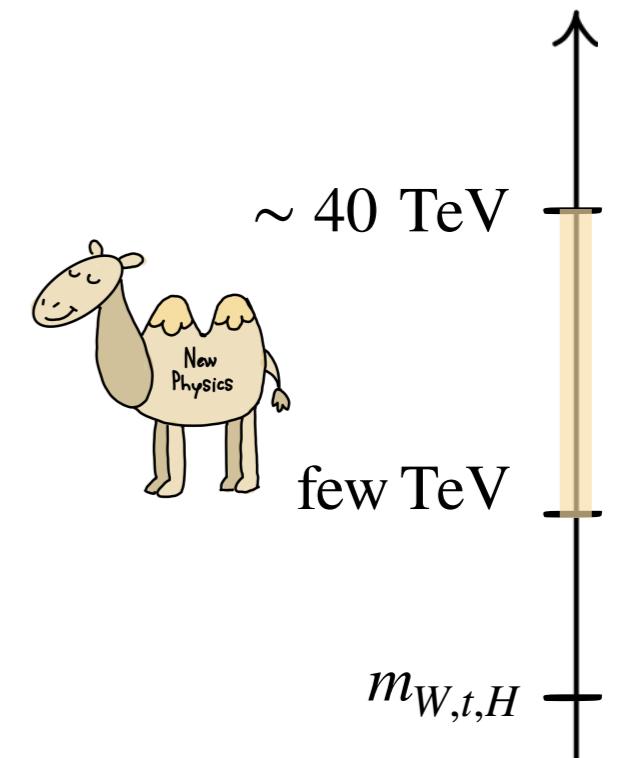
$$O_{10}^\mu = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu} \gamma^\mu \gamma_5 \mu)$$

$b \rightarrow sll$

- ▶ **NP size (scale)**



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



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

EFT lessons

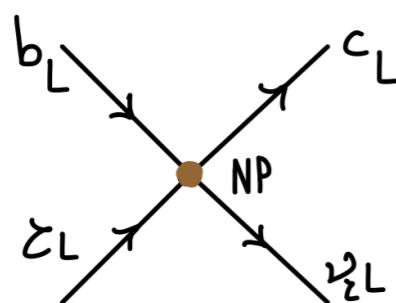
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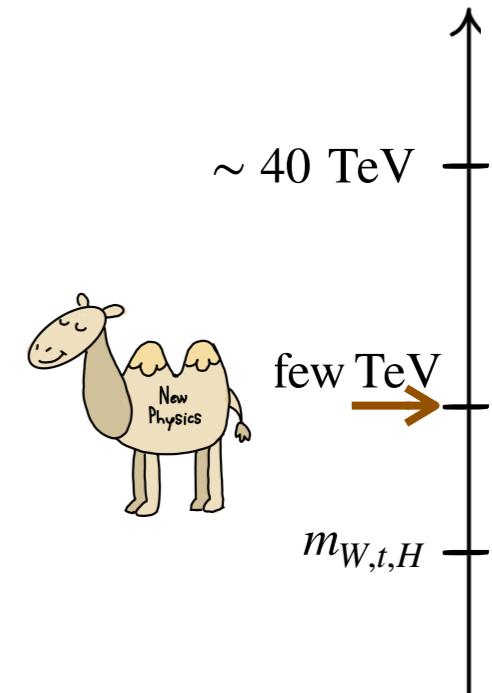
$$b \rightarrow cl\nu$$

- **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)**



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



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

Possible common origin

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

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

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

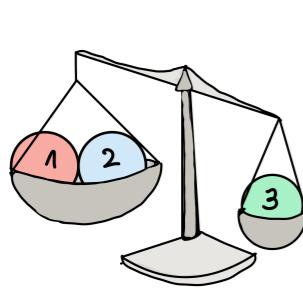
$$\mathcal{L} = -\frac{1}{v^2} \left(C_{\ell q}^{(3)} (\bar{\ell}_L \gamma^\mu \tau^a \ell_L) (\bar{q}_L \gamma^\mu \tau^a q_L) C_{\ell q}^{(1)} (\bar{\ell}_L \gamma^\mu \ell_L) (\bar{q}_L \gamma^\mu q_L) \right) \approx -\frac{2}{v^2} C_{LL} (\bar{q}_L \gamma^\mu l_L) (\bar{l}_L \gamma_\mu q_L)$$

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

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

Possible common origin

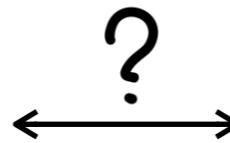
- Also, need a peculiar **flavor structure**: large NP couplings to 3rd family, smaller to 2nd and 1st. Similar to the only SM source of LFUV, the Yukawa couplings!



FLAVOR HIERARCHIES

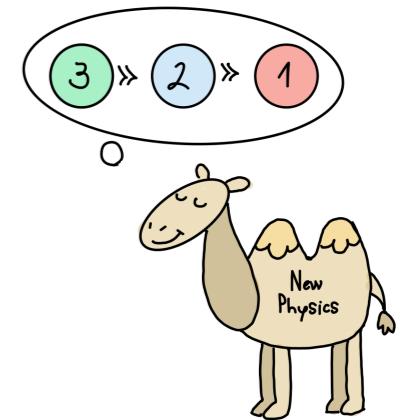
standard LFUV

$$y_3 \gg y_2 \gg y_1$$



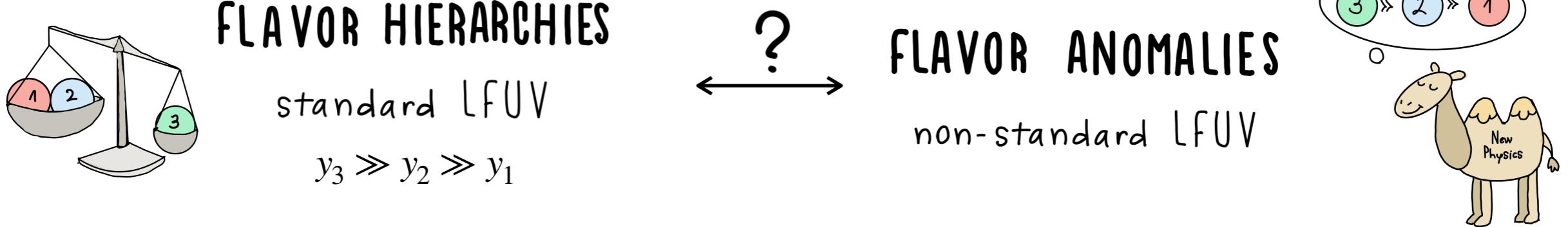
FLAVOR ANOMALIES

non-standard LFUV



Possible 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!



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

[Barbieri et al., 1105.3396,
1512.01560...]

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

Works for SM masses & mixings...

....and also for the anomalies!

$$Y = \begin{pmatrix} & \\ & \bullet \\ & \end{pmatrix}$$

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exact $U(2)^5$

NP coupled only to 3rd family

minimally broken $U(2)^5$

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

Possible common origin

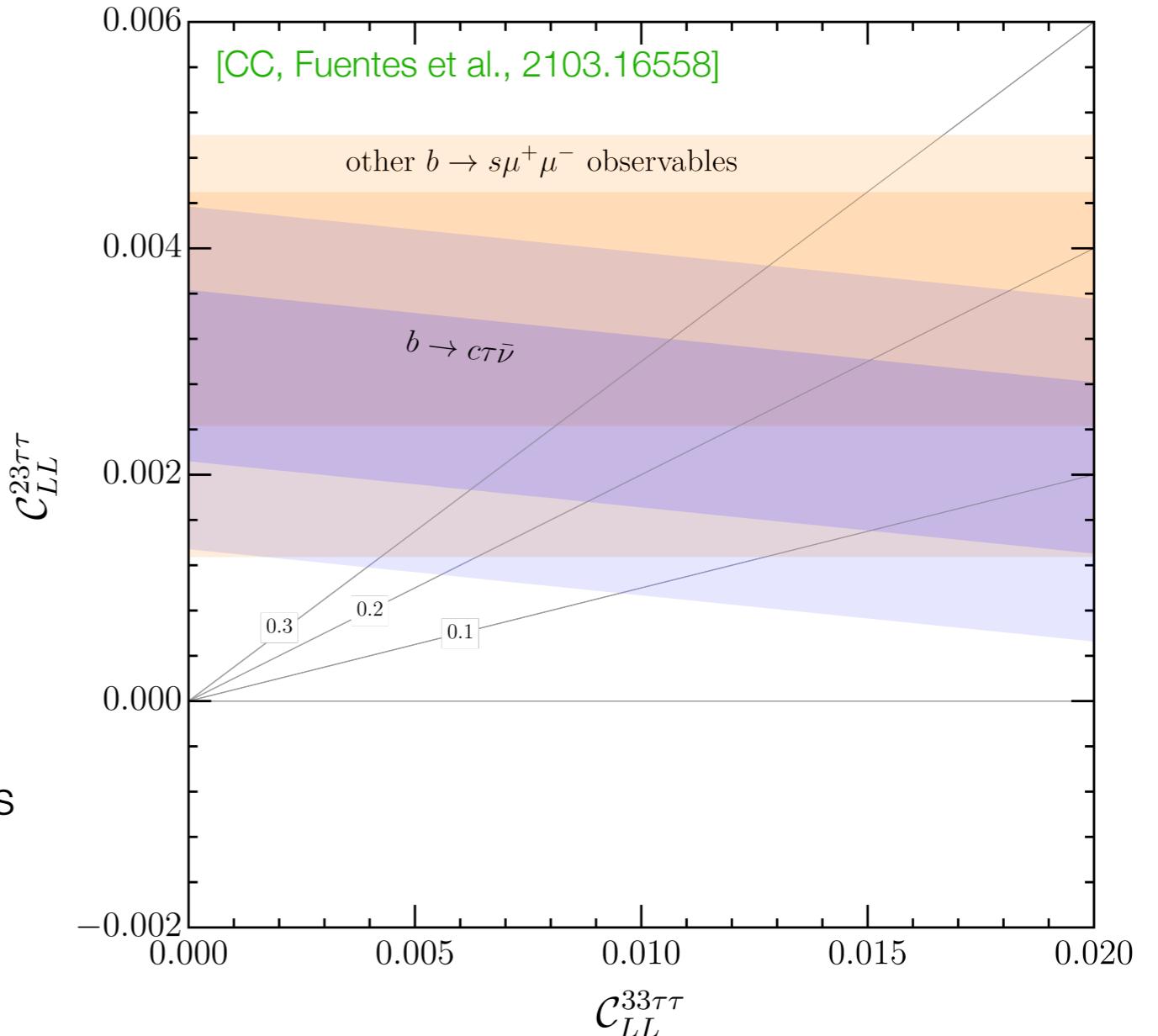
$$\mathcal{L}_{\text{EFT}}^{\text{NP}} = -\frac{2}{v^2} C_{LL}^{ij\alpha\beta} (\bar{q}_L^i \gamma^\mu q_L^\alpha)(\bar{l}_L^\beta \gamma_\mu l_L^j)$$

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

$b \rightarrow s \quad b \rightarrow c$

$C_{LL}^{33\tau\tau}$	~ 0.1
$C_{LL}^{23\tau\tau}$	$\sim \epsilon_q C_{LL}^{33\tau\tau}$
$C_{LL}^{23\mu\mu}$	$\sim \epsilon_q \epsilon_l^2 C_{LL}^{33\tau\tau}$

- good consistency between the anomalies



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

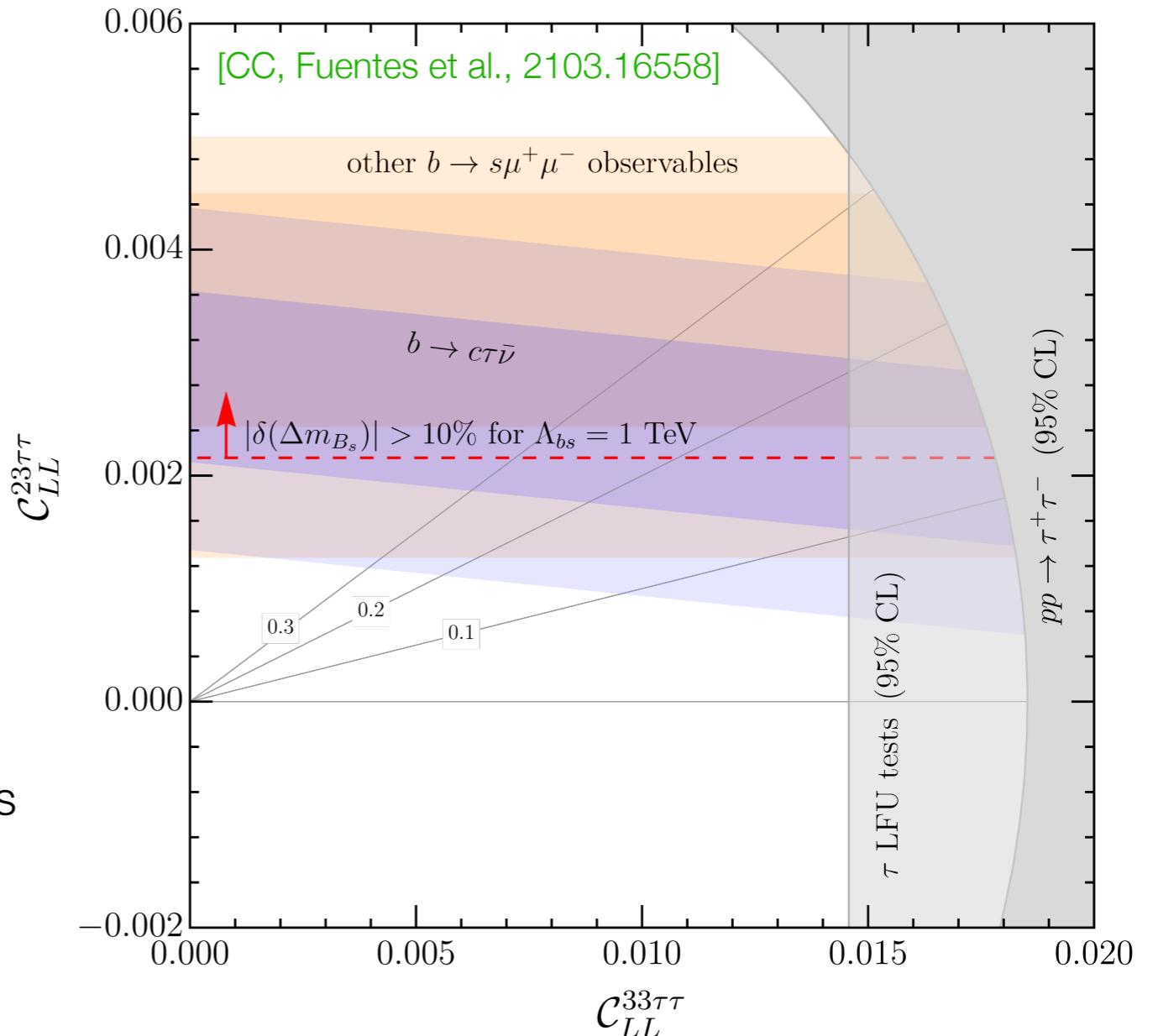
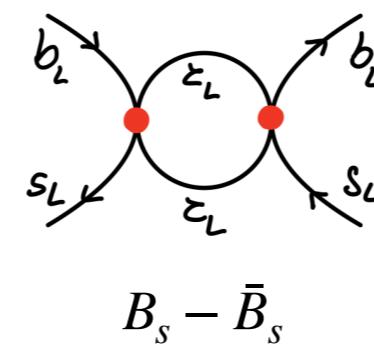
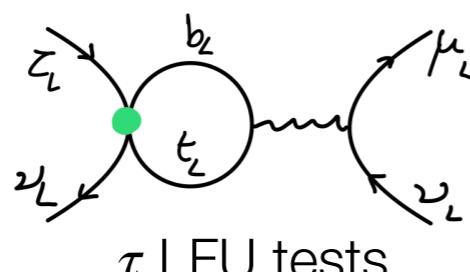
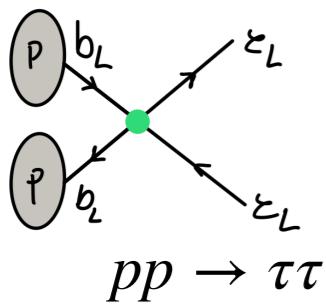
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- good consistency between the anomalies
- but several constraints (driven by $R_{D^{(*)}}$)



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

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]

- ▶ Three possibilities:

- $S_1 + S_3$ [Crivellin et al 1703.09226; Buttazzo et al. 1706.07808; Marzocca 1803.10972...]
- $R_2 + S_3$ [Bećirević 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...]

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

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

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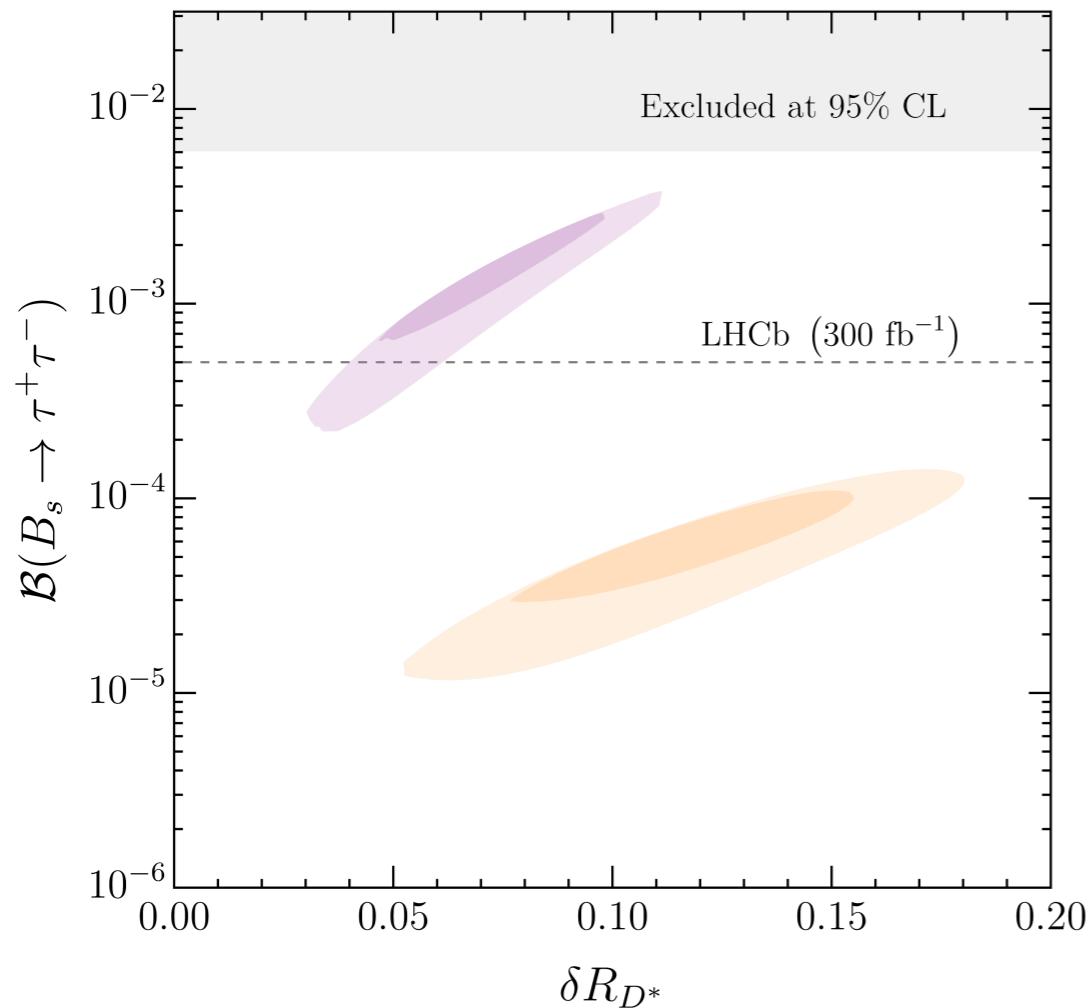
All have pros and cons:

- the vector leptoquark U_1 does not mediate $b \rightarrow s\nu\bar{\nu}$, $s \rightarrow d\bar{\nu}\nu$ 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: low-energy

Rich phenomenology at low & high energy:

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



no RH currents

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

with RH currents

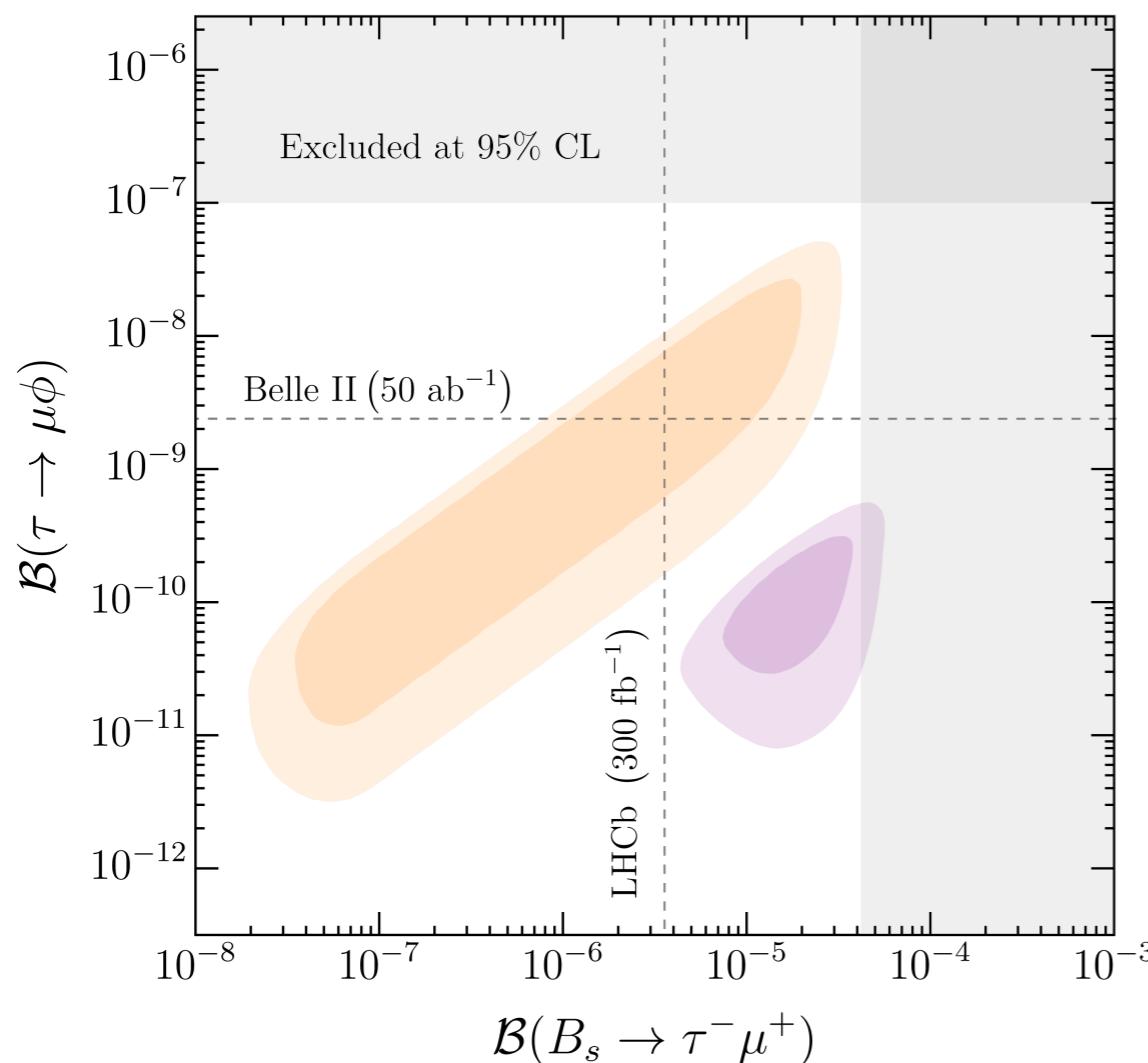
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The U_1 simplified model: low-energy

Rich phenomenology at low & high energy:

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

(driven by simultaneous presence of $R_{D^{(*)}}$ & $R_{K^{(*)}}$)



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

no RH currents

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

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

with RH currents

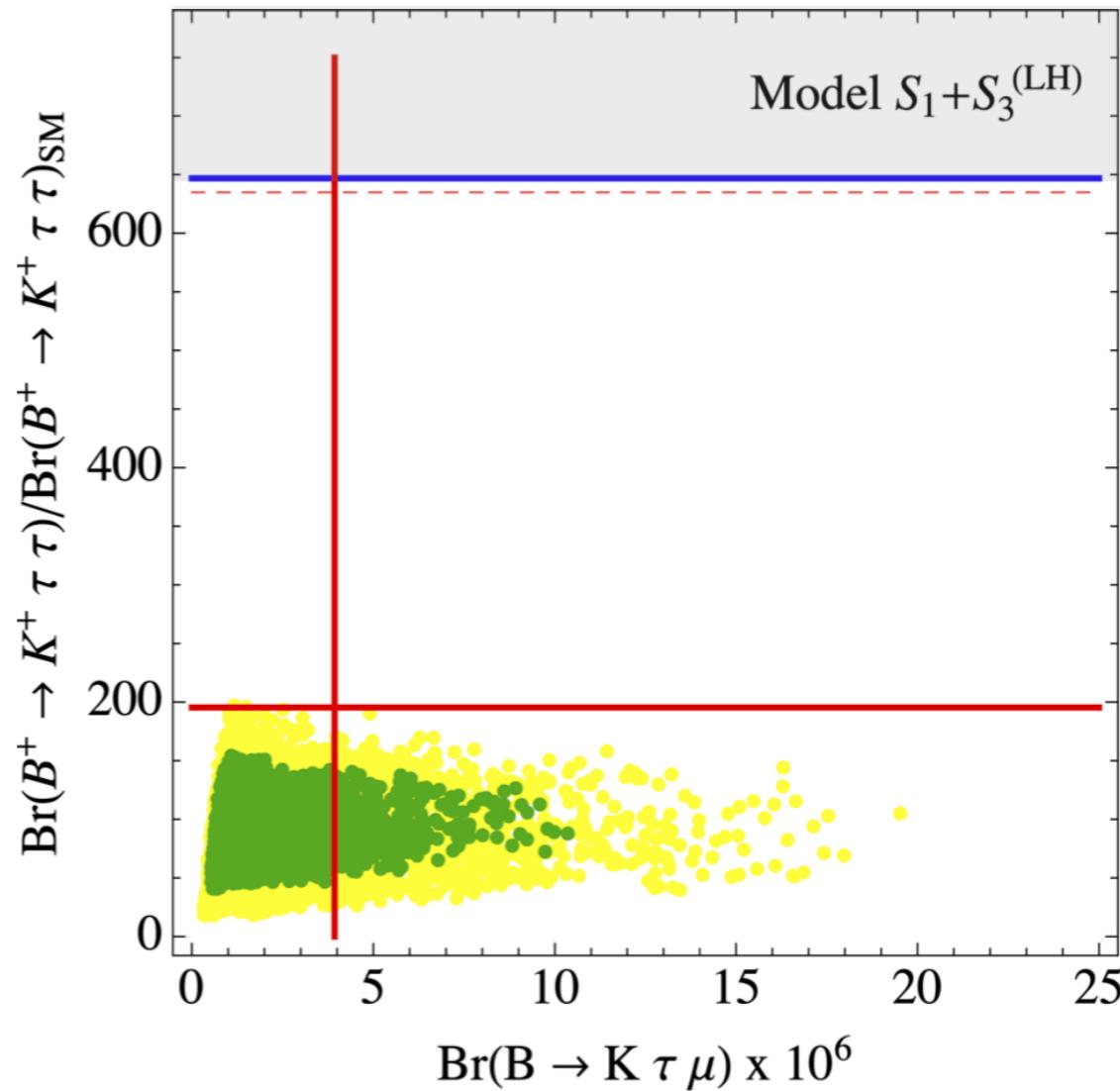
$$\mathcal{B}(B_s \rightarrow \tau\mu) \approx 1 \times 10^{-5}$$

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

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

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

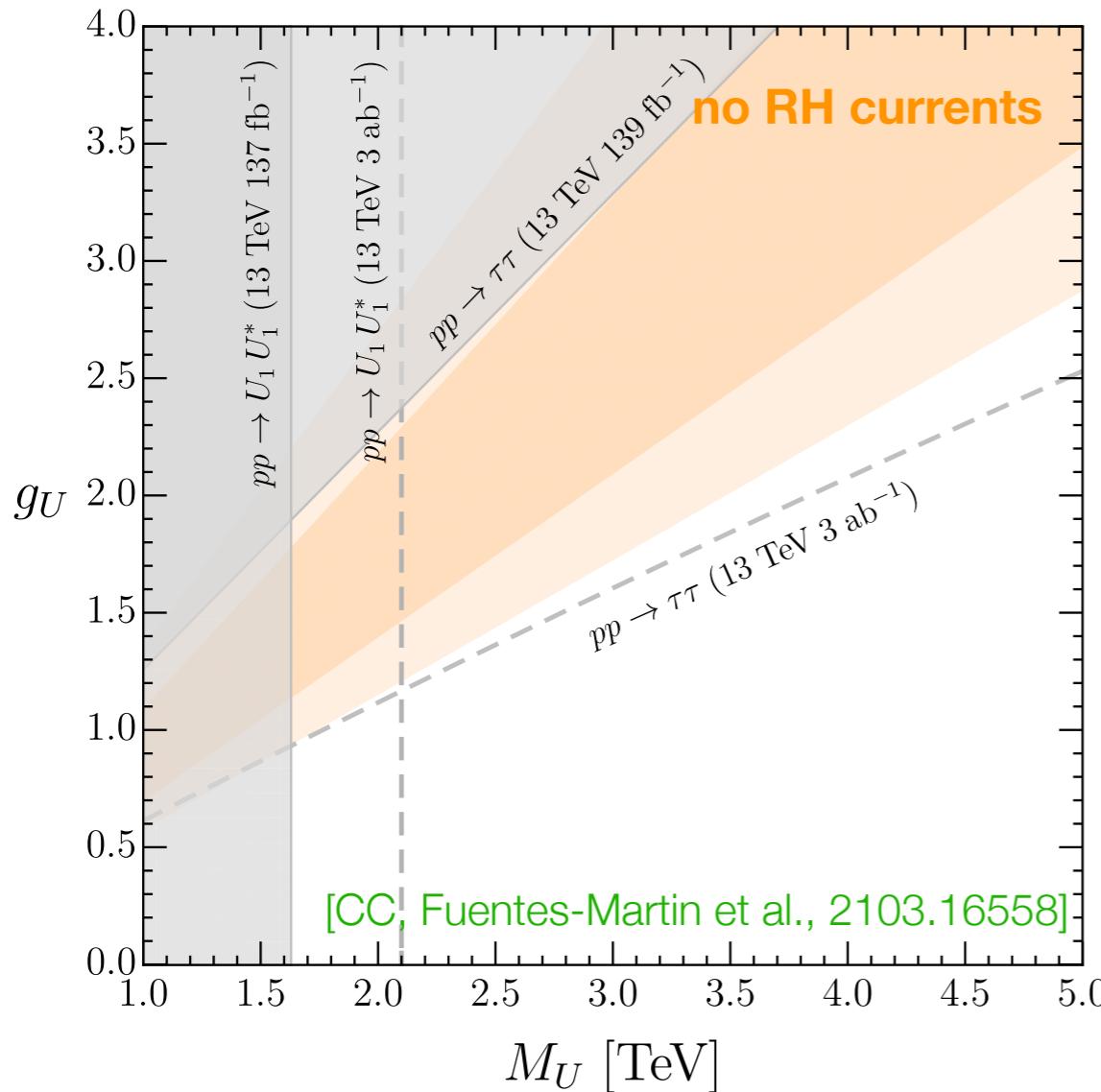
Similar signatures for the other simplified models, e.g. $S_1 + S_3$



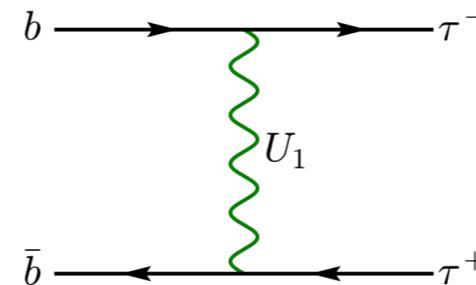
[Gherardi, Marzocca, Venturini 2008.09548]

The U_1 simplified model: high - pT

- The same interaction can be probed at high energy:



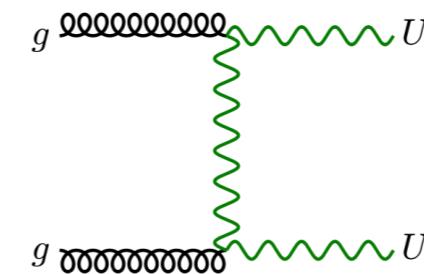
- $pp \rightarrow \tau\tau$ tails
(Drell-Yan t-channel exchange)



(Recast)
ATLAS
EXPERIMENT

[2002.12223](#)

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



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

$\mathcal{B}(U_1 \rightarrow b\tau^+) \approx 0.5$



[2012.04178](#)

→ 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...)

UV-completing the U_1 : the gauge path

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

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

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

$$SU(4) \sim \begin{pmatrix} G^a & U^\alpha \\ (U^\alpha)^* & Z' \end{pmatrix} \quad \psi_{L,R} = \begin{bmatrix} q_{L,R}^\alpha \\ q_{L,R}^\beta \\ q_{L,R}^\gamma \\ l_{L,R}^\delta \end{bmatrix} \quad \text{PS/SM} \ni U_1, Z'$$

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

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

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

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

Non-universality in 4321

How to make the U1 interactions with SM fermions non-universal, as required by the B anomalies?

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

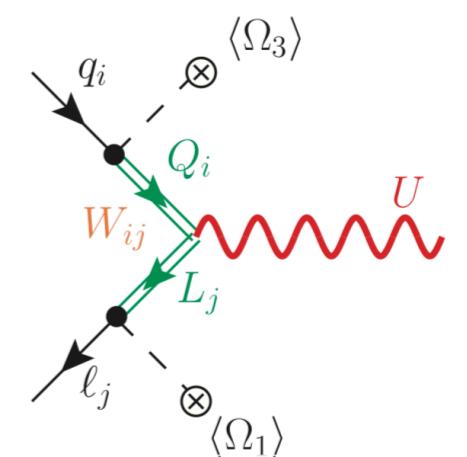
- **Non-universality via mixing with exotic vector-like fermions**

[Di Luzio et al. 1708.08450, 1808.00942...]

Gauge interactions are kept flavor universal:

SM fields are SM-like under 321, only VLF charged under 4

SM fermions interact with U_1 only via mixing with the VLF:
non-universal U_1 interactions with SM fields via hierarchical choice of
mixing angles (\rightarrow 3rd family has to be the “*most composite*”)

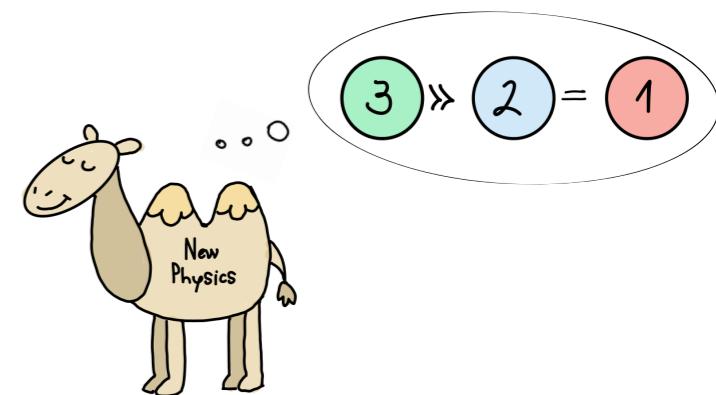


Depending on the charges of the VLF, the U1 couple to LH and/or RH SM fields.

Non-universality in 4321

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► Non-universality via flavor non-universal gauge interactions

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

3rd family special “by gauge”: light SM families SM-like under 321,
only 3rd family (& VLF) charged under 4

→ accidental $U(2)^5$ in gauge sector, broken by mixing with VLF

limit of exact $U(2)$ - only 3rd family (L+R) couples to the U_1
 - no 2-3 CKM mixing

$U(2)$ breaking generates - subleading U_1 couplings to light families
 - 2-3 CKM mixing

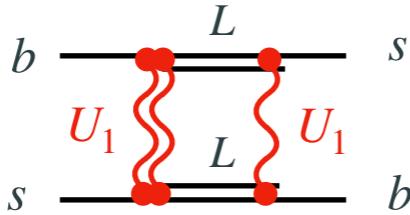
Connection flavor anomalies & hierarchies!

Importance of loop effects

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

- $B \rightarrow K\nu\bar{\nu}$ 20-50% enhancement over the SM, in the reach of Belle II

• B_s - \bar{B}_s mixing


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

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

VL lepton mass

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

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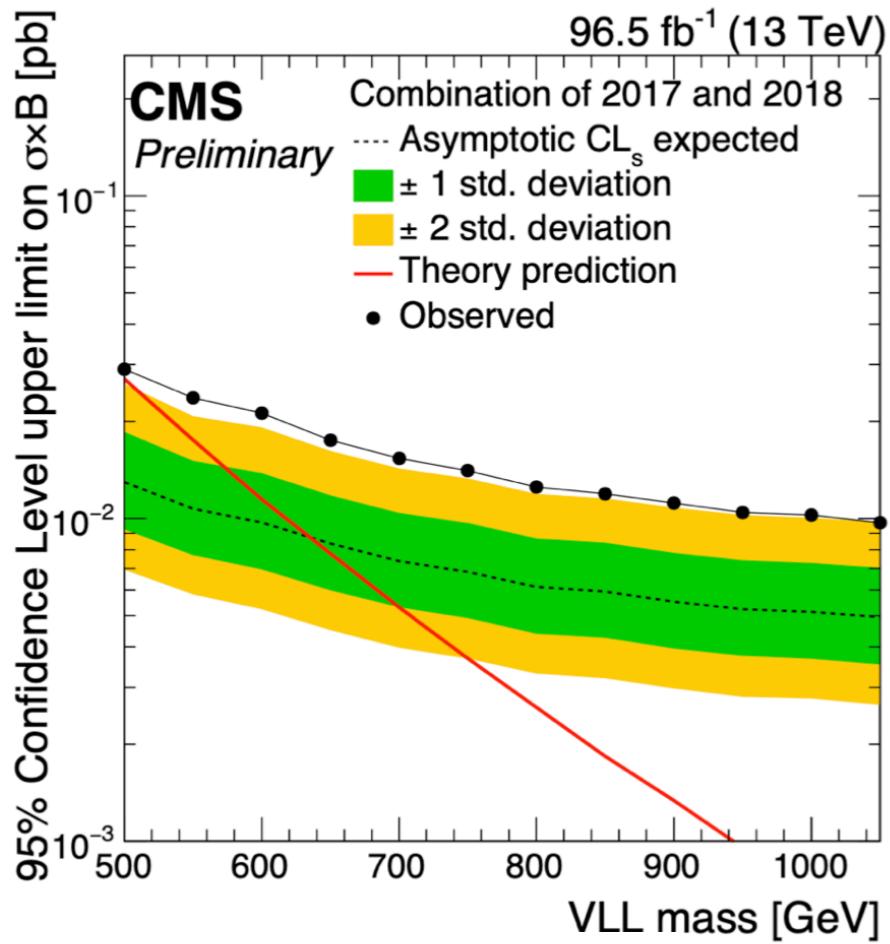
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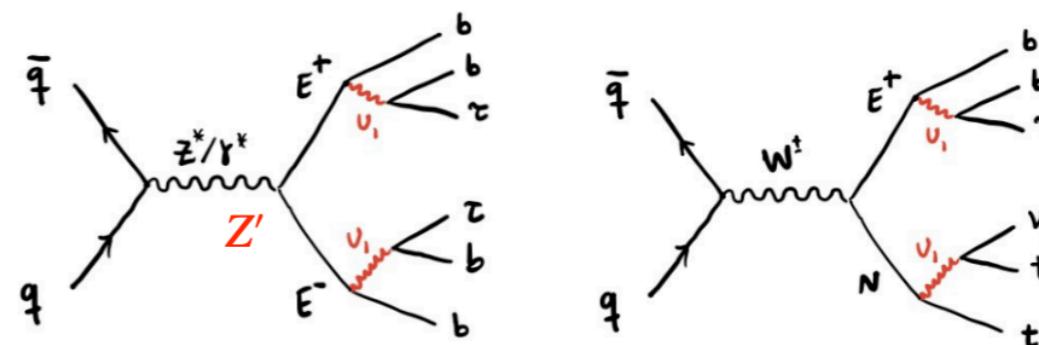
$U(2)_q$ breaking, fixed by $R_{D^{(*)}}$

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



[search assumes EW production only; preference for somehow larger masses once Z' production is included]

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

NP explanations for $b \rightarrow sll$ only

If we wish to explain only the NC anomaly, there are more options:

- ▶ Z' from gauged $U(1)_X$, e.g. $X = L_\mu - L_\tau$ [Altmannshofer, Gori, Pospelov, Yavin, 1403.1269
Altmannshofer, Gori, Pospelov, Yavin, 1406.2332 Crivellin,
D'Ambrosio, Heeck, 1501.00993 Altmannshofer, Yavin,
1508.07009
Crivellin, Fuentes-Martín, Greljo, Isidori, 1601.02703,
Allanach, Davighi, 1809.01158, 1905.10327....]

- ▶ Leptoquarks: U_1, S_3 [Hambye, Heeck; 1712.04871,
Davighi, Kirk, Nardecchia, 2007.15016,
Greljo, Stangl, Thomsen, 2103.13991, Greljo, Soreq,
Stangl, Thomsen, Zupan; 2107.07518]
e.g. “**muoquark**”:

charge S_3 under a lepton-flavored, anomaly-free $U(1)_X$ gauge symmetry

If $X = L_\mu - L_\tau$, $X_{S_3} = -1 \Rightarrow qS_3 l$ is gauge-invariant only for $l = \mu$;
automatic LFV suppression

Conclusions

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

- ▶ Taken together, they point to TeV-scale leptoquark(s) coupled dominantly to the 3rd family.
 - rich phenomenology; can be tested complementarily at low- and high-E exp.
 - flavor non-universal gauge interactions?
- ▶ Consistent picture, but present data in $b \rightarrow c\tau\nu$ 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!

Back up

The U_1 simplified model

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

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

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

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

$$b \rightarrow s\tau\tau \text{ [tree]}$$

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

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

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

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

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

Two interesting benchmarks:

1. no RH currents $[\beta_{b\tau}^R = 0]$
2. “max” RH currents $|\beta_{b\tau}^R| = |\beta_{b\tau}^L| = 1$

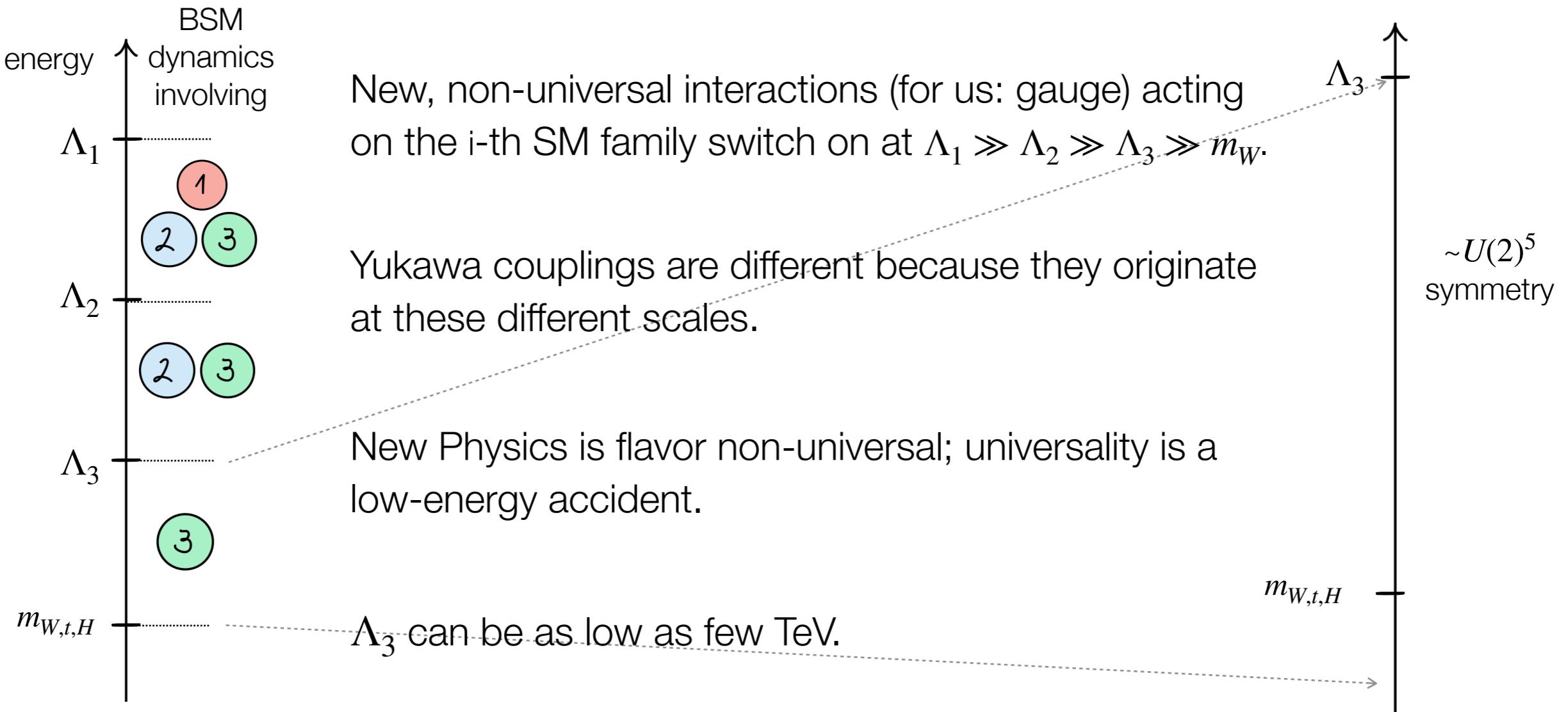
[models with 3rd family quark-lepton unification]

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

A three-scale picture

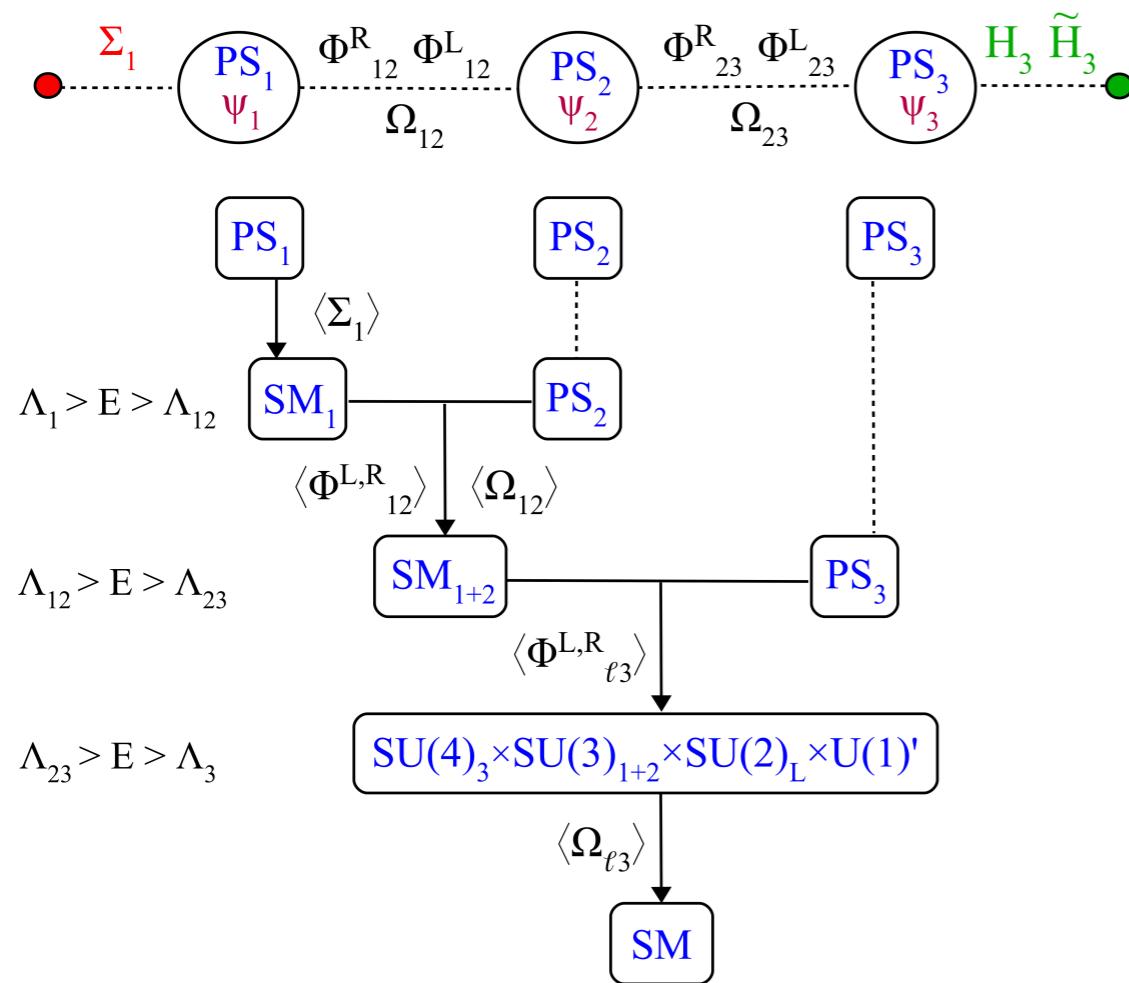
[Barbieri, 2103.15635,
Bordone, CC, Fuentes, Isidori 1712.01368
Panico, Pomarol, 1603.06609 Dvali, Shiftman, '00, ...]

B anomalies might hint at a three-scale picture:

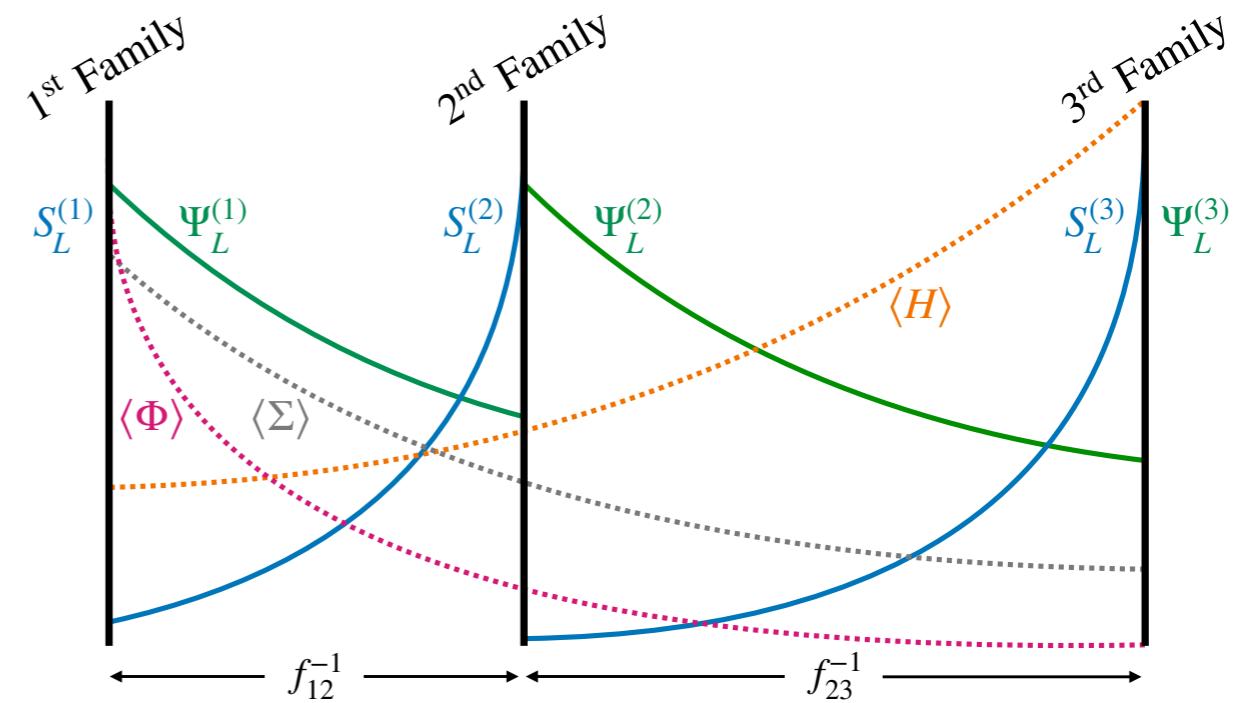


UV completing 4321

► PS³: 4D three-site model



► Warped extra dimension



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

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

[Bordone, CC, Fuentes, Isidori 1712.01368]