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Deconstructing flavor anomalously

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Based on: 2402.09507

(with Javier Fuentes-Martin)

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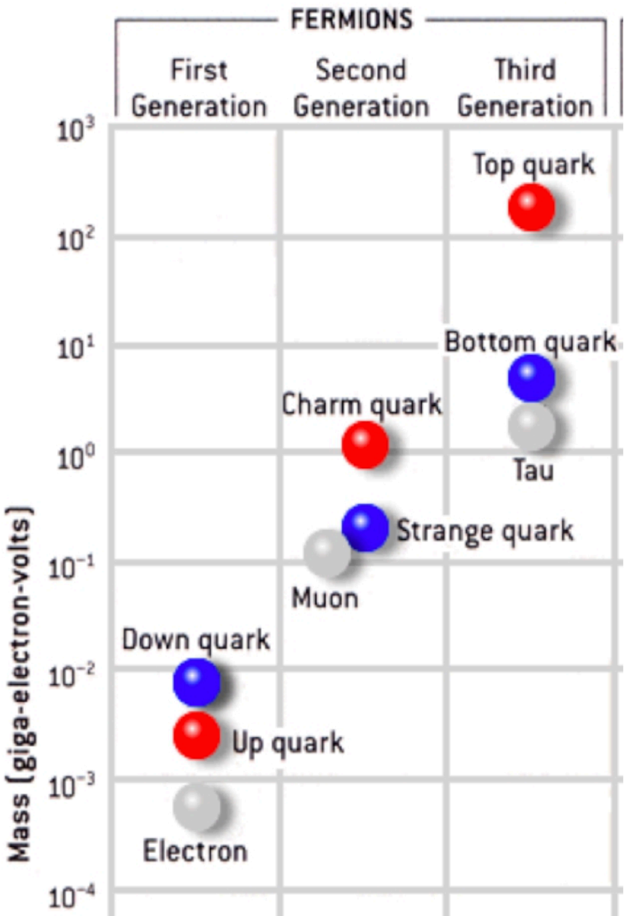
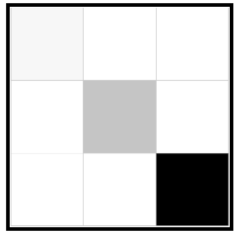
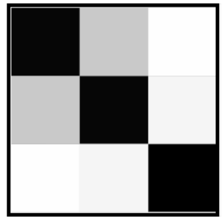
Deconstructing **flavor** anomalously

The flavor puzzle

- **Flavor puzzle**: very hierarchical structures



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

$V_{\mathrm{CKM}} \sim$ 

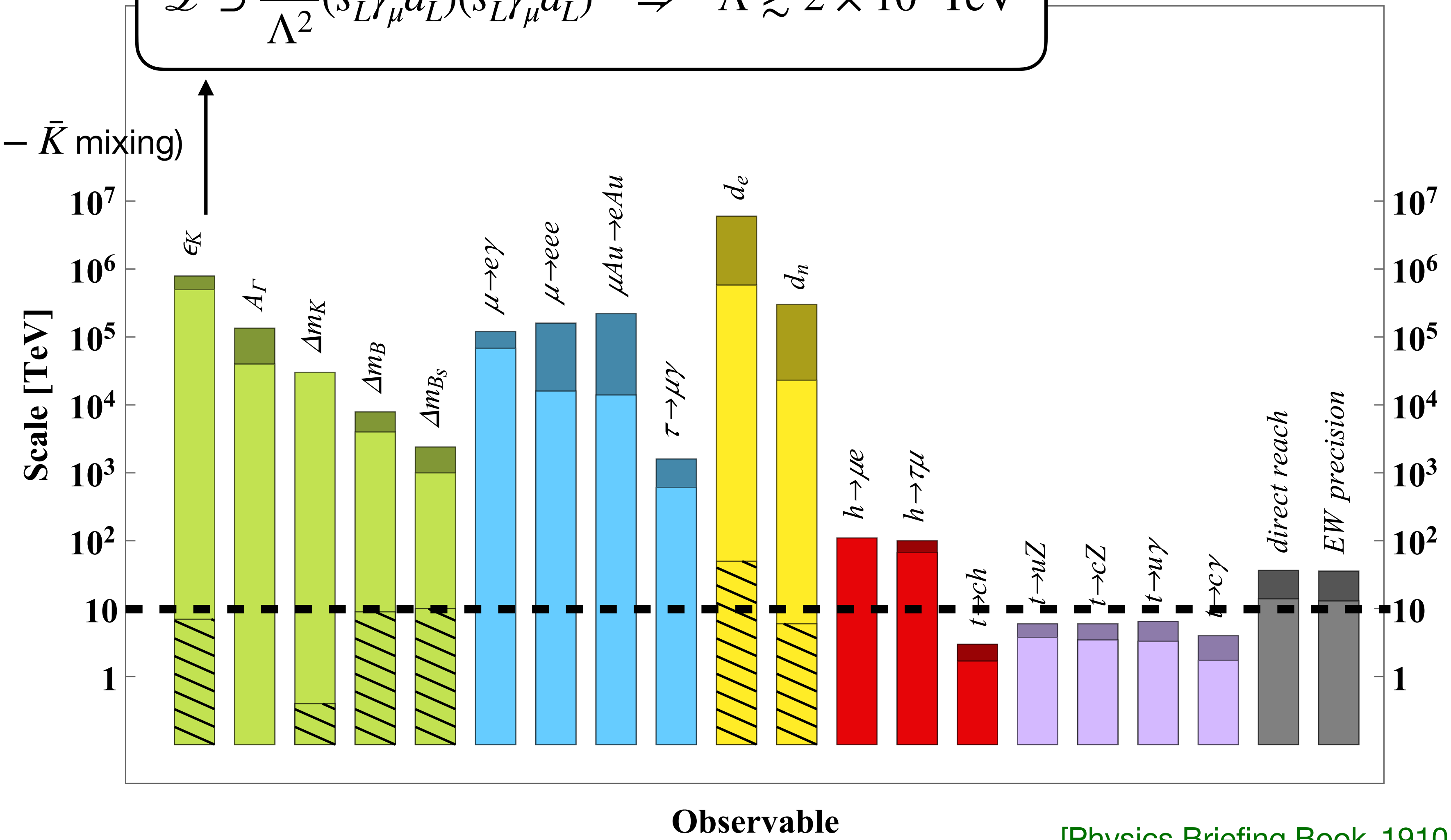
$$|V_{\mathrm{CKM}}| = \begin{bmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 0.0080 \pm 0.0003 & 0.0388 \pm 0.0011 & 1.013 \pm 0.030 \end{bmatrix}$$

New Physics bounds

$$\mathscr{L} \supset \frac{e^{i\phi}}{\Lambda^2}(\bar{s}_L\gamma_\mu d_R)(\bar{s}_R\gamma_\mu d_L) \quad \Rightarrow \quad \Lambda \gtrsim 5\times 10^5\,\text{TeV}$$

$$\mathscr{L} \supset \frac{e^{i\phi}}{\Lambda^2}(\bar{s}_L\gamma_\mu d_L)(\bar{s}_L\gamma_\mu d_L) \quad \Rightarrow \quad \Lambda \gtrsim 2\times 10^4\,\text{TeV}$$

($K-\bar{K}$ mixing)



[Physics Briefing Book, 1910.11775]

Flavor symmetries of SM

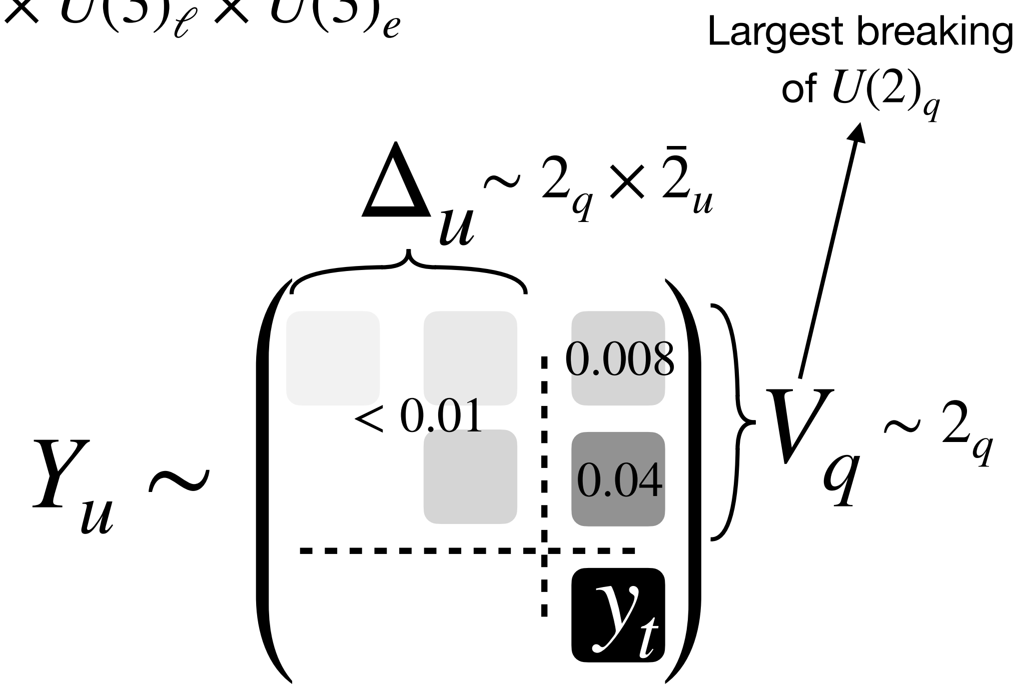
- Flavor symmetry $U(3)^5$, only broken by Yukawas:

$$\mathscr{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\,\mu\nu} + \bar{\psi}_a \not{D} \psi_a + |D_\mu H|^2 - V(H) + (Y_{ab}\,\bar{\psi}^a_L\, H\, \psi^b_R + \mathrm{h.c.})$$

$$U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$$

- $Y_{u,d,e}$ very hierarchical:

- Protection in FCNC (GIM).



Flavor symmetries of SM

- To leading order:

$$U(3)^5 \xrightarrow[\text{Top Yuk.}]{} U(2)_q \times U(2)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$$

$$U(3)^5 \xrightarrow[\text{3rd fam. Yuk.}]{} U(2)^5$$

- Protection in FCNC (GIM).

A good way to improve flavor bounds on NP is to preserve the same flavor symmetries.

Flavor deconstruction as origin of the flavor hierarchies

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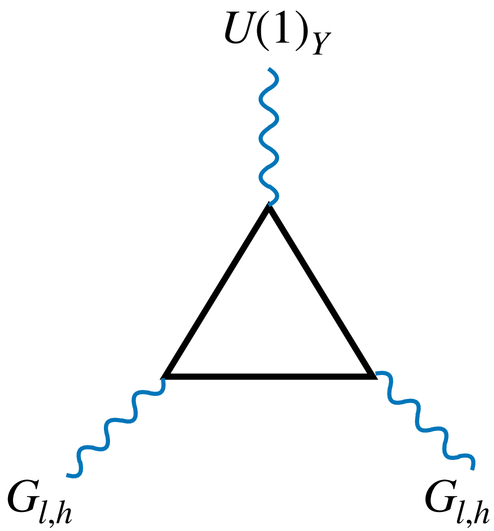
Deconstructing flavor anomalously

Non-universal gauge extensions

$$G_l \times G_h \times G_U \xrightarrow{\langle \Phi \rangle \neq 0} G_{\rm SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$$

Splitting SM fields, our BSM model can have the required accidental symmetries

- Careful with gauge anomalies: deconstruction family by family



Otherwise…

$$\sum_{f \sim G_{l,h}} y_f \neq 0$$

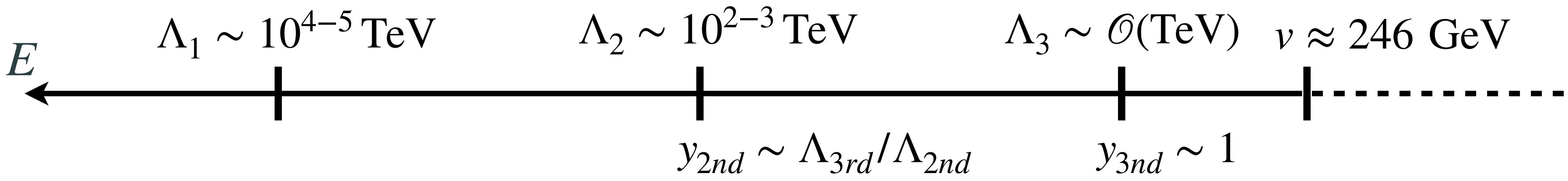
Non-universal gauge extensions

$$\underbrace{G_1 \times G_2}$$

$$\Big\downarrow \sim 10^{2-3}\,\text{TeV}$$

$$\underset{\substack{\downarrow \\ 1,2}}{G_l} \times \underset{\substack{\downarrow \\ 3}}{G_h} \times \underset{\substack{\downarrow \\ \text{All}}}{G_U} \xrightarrow[\sim\,\text{TeV}\,!!]{\langle \Phi \rangle \neq 0} G_{\text{SM}} = SU(3)_c \times SU(2)_L \times U(1)_Y$$

- Multiscale picture for flavor:



[Berezhiani, Rattazz, hep-ph/9212245; Dvali, Shiftman, hep-ph/0001072; Panico, Pomarol, 1603.06609; Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368; Barbieri, 2103.15635]

Non-universal gauge extensions

- Deconstructions: $\mathscr{L} \supset \bar{\psi}_L Y H \psi_R$

$$U(1)_Y = [U(1)_{B-L} \times U(1)_R]_{\rm diag}$$
$$SU(4)_{PS} \supset SU(3)_c \times U(1)_{B-L}$$

$$SU(4)^l_{PS} \times SU(4)^h_{PS} \times \dots \qquad Y \sim \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$$SU(2)^l_L \times SU(2)^h_L \times \dots \qquad Y \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}$$

$$U(1)^l_R \times U(1)^h_R \times \dots \qquad Y \sim \begin{pmatrix} 0 & 0 & \times \\ 0 & 0 & \times \\ 0 & 0 & \times \end{pmatrix}$$

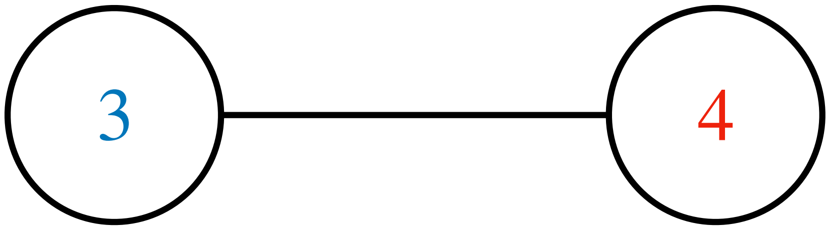
- Higher scale NP can generate suppressed extra elements

An example to play: 4321

[Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368; Greljo, Stefanek, 1802.04274; Allwicher, Isidori, JML, Selimović, Stefanek, 2302.11584]

$$SU(4)^h_{PS} \times SU(3)^l_c \times SU(2)_L \times \underbrace{U(1)_X}_{[U(1)_R \times U(1)_{(B-L)^l}]_{\rm diag}} \to G_{\rm SM}$$

$SU(3)^l_c \times U(1)_{(B-L)^l}$ $\qquad$ $SU(4)^h_{PS}$



$q_L^{1,2}$ $\quad$ $\ell_L^{1,2}$

$u_R^{1,2}$ $\quad$ $e_R^{1,2}$

$d_R^{1,2}$

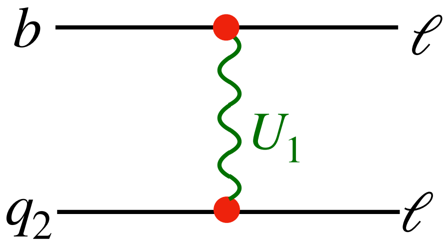
(q_L^3, ℓ_L^3)

(t_R, ν_R)

(b_R, τ_R)

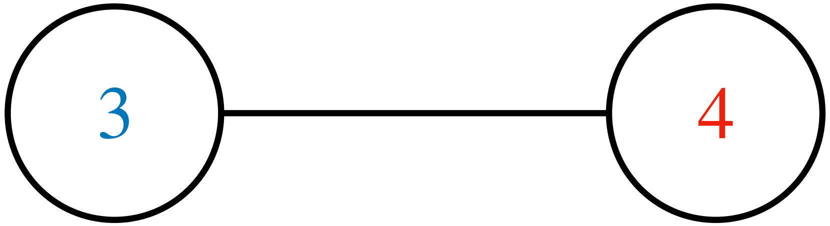
$$SU(4)^h_{PS} \sim \left(\begin{array}{c:c} G^a & U^\alpha \\ \hdashline (U^\alpha)^* & Z' \end{array}\right)$$

It gives a TeV leptoquark with large couplings to the 3rd family: well studied in the context of B anomalies



An example to play: 4321

$SU(3)^l_c \times U(1)_{(B-L)^l}$ $\quad$ $SU(4)^h_{PS}$



$q_L^{1,2}$ $\quad \ell_L^{1,2}$

$u_R^{1,2}$ $\quad e_R^{1,2}$

$d_R^{1,2}$

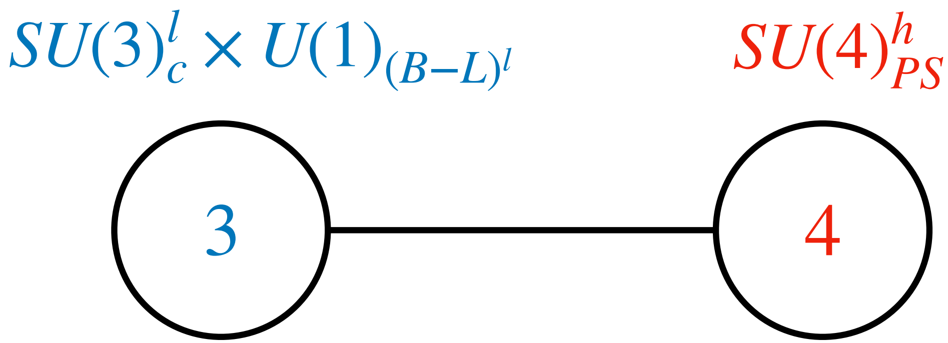
(q_L^3, ℓ_L^3)

(t_R, ν_R)

(b_R, τ_R)

Accidental $U(2)_q \times U(2)_u \times U(2)_d \times U(2)_\ell \times U(2)_e$ symmetry

An example to play: 4321



$q_L^{1,2}$ $\ell_L^{1,2}$

$u_R^{1,2}$ $e_R^{1,2}$

$d_R^{1,2}$ $b_R,\ \tau_R$

(q_L^3, ℓ_L^3)

(t_R, ν_R)

Accidental $U(2)_q \times U(2)_u \times U(3)_d \times U(2)_\ell \times U(3)_e$ symmetry

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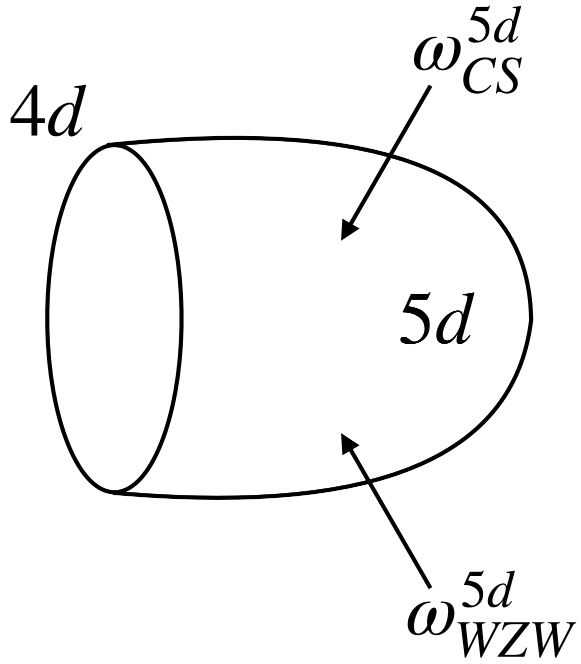
Deconstructing flavor anomalously

WZW terms to cure gauge anomalies

- Anomalies: $\delta\Gamma = \mathscr{A}(A)$

- Chern-Simons (CS) in 5d cancels the anomaly:

$$\omega_{CS}(A) \quad / \quad \delta\omega_{CS} = -\mathscr{A}$$



- Wess-Zumino-Witten (WZW) terms:

$$\omega'_{WZW}(A,\alpha) \quad / \quad \mathrm{d}\omega'_{WZW} = -\mathrm{d}\omega_{CS} \quad \& \quad \delta\omega'_{WZW} = 0$$

$$\omega_{WZW} = \omega'_{WZW} + \omega_{CS} \Rightarrow \mathrm{d}\omega_{WZW} = 0 \quad \& \quad \delta\omega_{WZW} = -\mathscr{A}$$

Total derivative: it describes dynamics in 4d

[Wess, Zumino, 1971, Witten, 1983]

UV to cure gauge anomalies

- Introducing new fermionic degrees of freedom: anomalons? (typically, fractional charges or unjustified suppressed masses).

- If the breaking to the SM is triggered by a composite sector:

Condensate

$$G_h \times G_l \times G_U \xrightarrow[\sim \text{TeV}]{\langle \Phi \rangle \neq 0} G_{\text{SM}}$$

… via this sector (like in QCD).

- Tempting: no extra scalars and radiatively stable.

[Fuentes-Martín, Stangl, 2004.11376, Chung, Goertz, 2311.17169, Fuentes-Martín, JML, 2402.09507]

The QCD example

- If there is no Higgs…

$U(1)_Y$

$SU(2)_L \times U(1)_Y \to U(1)_{\mathrm{EM}}$

	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
(u_L, d_L)	**3**	**2**	**1**	1/6
(u_R, d_R)	**3**	**1**	**2**	1/6
(ν_L, e_L)	**1**	**2**	**1**	-1/2
(ν_R, e_R)	**1**	**1**	**2**	-1/2

$\langle \bar{u}_L u_R + \bar{d}_L d_R \rangle \sim \Lambda_{\mathrm{QCD}}$

It confines at Λ_{QCD} and pions eaten by EW gauge bosons

$$\sum_{\text{LH leptons}} q_{B-L} \neq 0$$

Anomaly contribution from leptons (e.g, in $SU(2)_L - SU(2)_L - U(1)_Y$) only cancelled by quarks

$\boxed{\text{Same mechanism to BSM}}$

Realization in 4321

$$SU(4)^h_{PS} \times SU(3)^l_c \times SU(2)_L \times U(1)_X \times SU(N_{\rm HC}) \xrightarrow[\langle \bar{\zeta}_L \zeta_R \rangle \neq 0]{} G_{\rm SM} \times SU(N_{\rm HC})$$

4 hyper-quarks

	$SU(N_{\rm HC})$	$SU(4)^h_{PS}$	$SU(4)^l_{PS}$	$U(1)_R$
ζ_L	$\square$	**1**	**4**	
ζ_R	$\square$	**4**	**1**	
(q^3_L, ℓ^3_L)	**1**	**4**	**1**	0
(t_R, ν^3_R)	**1**	**4**	**1**	1/2
(b_R, τ_R)	**1**	**1**	**4**	-1/2
$(q^{1,2}_L, \ell^{1,2}_l)$	**1**	**1**	**4**	0
$(u^{1,2}_R, \nu^{1,2}_R)$	**1**	**1**	**4**	1/2
$(d^{1,2}_R, e^{1,2}_R)$	**1**	**1**	**4**	-1/2

$SU(4)^l_{PS} \times SU(4)^h_{PS}$ are the *flavor* symmetries of the hyper-quarks

[Fuentes-Martín, Stangl, 2004.11376; Fuentes-Martín, JML, 2402.09507]

Realization in 4321

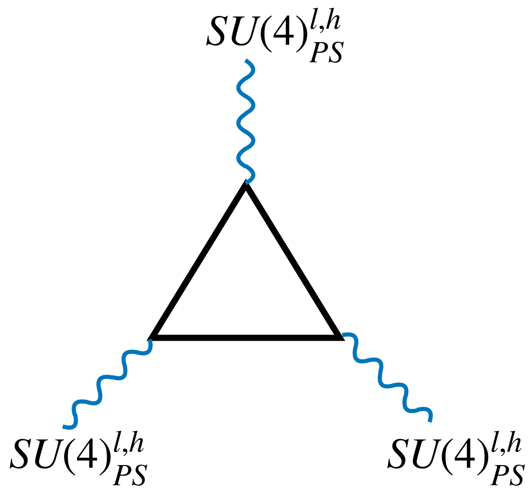
$$SU(4)^h_{PS} \times SU(3)^l_c \times SU(2)_L \times U(1)_X \times {\color{red} SU(N_{\rm HC})} \xrightarrow[\langle \bar{\zeta}_L \zeta_R \rangle \neq 0]{} G_{\rm SM} \times {\color{red} SU(N_{\rm HC})}$$

4 hyper-quarks

	$SU(N_{\rm HC})$	$SU(4)^h_{PS}$	$SU(4)^l_{PS}$	$U(1)_R$
ζ_L	$\square$	**1**	**4**	
ζ_R	$\square$	**4**	**1**	
(q^3_L, ℓ^3_L)	**1**	**4**	**1**	0
(t_R, ν^3_R)	**1**	**4**	**1**	1/2
(b_R, τ_R)	**1**	**1**	**4**	-1/2
$(q^{1,2}_L, \ell^{1,2}_l)$	**1**	**1**	**4**	0
$(u^{1,2}_R, \nu^{1,2}_R)$	**1**	**1**	**4**	1/2
$(d^{1,2}_R, e^{1,2}_R)$	**1**	**1**	**4**	-1/2
${\color{red}(N_{\rm HC}-1) \times \chi_L}$	**1**	**4**	**1**	0
${\color{red}(N_{\rm HC}-1) \times \chi_R}$	**1**	**1**	**4**	0

$SU(4)^l_{PS} \times SU(4)^h_{PS}$ are the *flavor* symmetries of the hyper-quarks

Cubic anomalies:



[Fuentes-Martín, Stangl, 2004.11376; Fuentes-Martín, JML, 2402.09507]

Realization in 4321

$$SU(4)^h_{PS} \times SU(3)^l_c \times SU(2)_L \times U(1)_X \times {\color{red}SU(N_{\rm HC})} \xrightarrow[\langle \bar{\zeta}_L \zeta_R \rangle \neq 0]{} G_{\rm SM} \times {\color{red}SU(N_{\rm HC})}$$

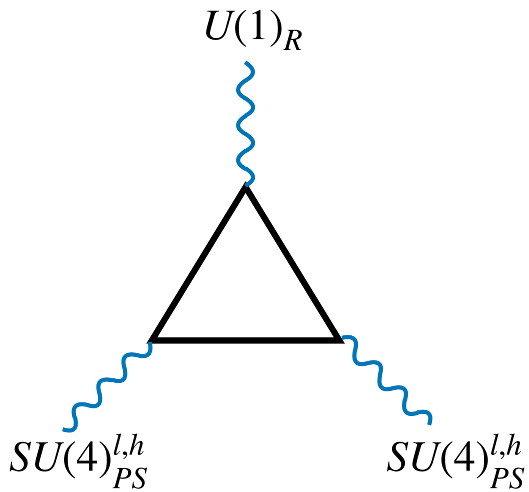
4 hyper-quarks

	$SU(N_{\rm HC})$	$SU(4)^h_{PS}$	$SU(4)^l_{PS}$	$U(1)_R$
ζ_L	$\square$	**1**	**4**	${\color{red}-1/2N_{\rm HC}}$
ζ_R	$\square$	**4**	**1**	${\color{red}-1/2N_{\rm HC}}$
(q^3_L, ℓ^3_L)	**1**	**4**	**1**	0
(t_R, ν^3_R)	**1**	**4**	**1**	1/2
(b_R, τ_R)	**1**	**1**	**4**	-1/2
$(q^{1,2}_L, \ell^{1,2}_l)$	**1**	**1**	**4**	0
$(u^{1,2}_R, \nu^{1,2}_R)$	**1**	**1**	**4**	1/2
$(d^{1,2}_R, e^{1,2}_R)$	**1**	**1**	**4**	-1/2
$(N_{\rm HC}-1) \times \chi_L$	**1**	**4**	**1**	0
$(N_{\rm HC}-1) \times \chi_R$	**1**	**1**	**4**	0

Anomaly free!

$SU(4)^l_{PS} \times SU(4)^h_{PS}$ are the *flavor* symmetries of the hyper-quarks

Mixed anomalies:



$$\sum_{f \sim SU(4)^{l,h}_{PS}} q^R_f = 0$$

UV completion for charge quantisation

$$SU(N_{\mathrm{HC}}) \times U(1)_{\mathrm{HC}} \xrightarrow{\quad \Lambda > \langle \bar{\zeta}_L \zeta_R \rangle \quad} U(1)_R$$

		$SU(N_{\mathrm{HC}}+1)$	$SU(4)^h_{PS}$	$SU(4)^l_{PS}$	$SU(2)_R$
	$\Xi_L = (\zeta_L, U_L)$	$\square$	**1**	**4**	**1**
$\psi_R^{3u} = (t_R, \nu_R^3)$	$\Xi_R = (\zeta_R, \psi_R^{3u})$	$\square$	**4**	**1**	**1**
	(q_L^3, ℓ_L^3)	**1**	**4**	**1**	**1**
$\psi_R^{3d} = (b_R, \tau_R)$	$\psi_R^3 = (U_R, \psi_R^{3d})$	**1**	**1**	**4**	**2**
	$(q_L^{1,2}, \ell_L^{1,2})$	**1**	**1**	**4**	**1**
	$(q_R^{1,2}, \ell_R^{1,2})$	**1**	**1**	**4**	**2**
	$(N_{\mathrm{HC}}-1)\times\chi_L$	**1**	**4**	**1**	0
	$(N_{\mathrm{HC}}-1)\times\chi_R$	**1**	**1**	**4**	0

Anomalous t_R is an hyper-lepton of the hyper-quarks à la Pati-Salam!!

Other applications

- Another useful flavor symmetry to address simultaneously quark and lepton hierarchies:

$$U(2)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(2)_e$$

[Antusch, Greljo, Stefanek, Thomsen, 2311.09288]

- Possible to achieve by deconstructing anomalously the EW group.

[Work in progress]

- Connection with composite Higgs scenarios?

[Work in progress]

Conclusions

- An interesting way to address flavor hierarchies at a (relatively) low scale is by deconstructing the gauge group.
- In some cases it is interesting to do an anomalous charging of the SM fermions: mixed anomalies with the $U(1)$ group.
- We have proposed a mechanism for charging same-family fermions into different factors of a deconstructed gauge theory in a way that gauge anomalies are avoided.
- The mechanism relies in the inclusion of a strongly-coupled sector, responsible of both anomaly cancellation and the breaking of the non-universal gauge symmetry.

Thank you!

Backup

Non-universal gauge extensions

- Examples:

$SU(3)^h_c \times SU(3)^l_c \times SU(2)_L \times U(1)_Y$ [Chivukula, Simmons, Vignaroli, 1302.1069]

$SU(4)^h_{PS} \times SU(3)^l_c \times SU(2)_L \times U(1)_X$ [Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368; Greljo, Stefanek, 1802.04274; Crosas, Isidori, JML, Selimović, Stefanek, 2203.01952; Allwicher, Isidori, JML, Selimović, Stefanek, 2302.11584]

$SU(4)^h_{PS} \times SU(2)^h_R \times SU(3)^l_c \times U(1)^l_Y \times SU(2)_L$ [Davighi, Isidori, 2303.01520]

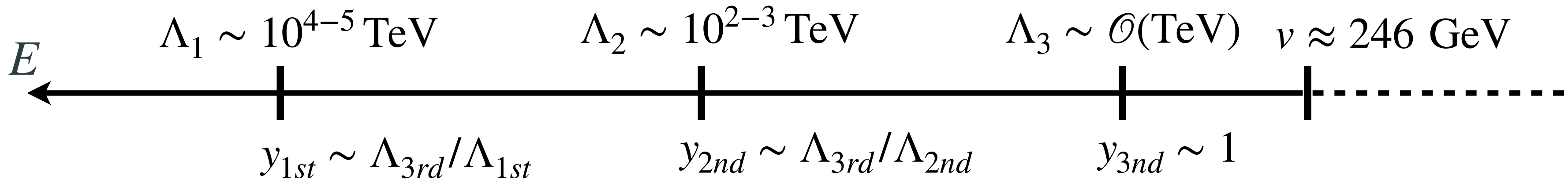
$U(1)^h_Y \times U(1)^l_Y \times SU(3)_c \times SU(2)_L$ [Fernández-Navarro, King, 2305.07690; Davighi, Stefanek, 2305.16280]

$SU(2)^h_L \times SU(2)^l_L \times SU(3)_c \times U(1)_Y$ [Davighi, Gosnay, Miller, Renner 2312.13346; [Capdevila, Crivellin, JML, Pokorski, 2401.00848]

Multiscale flavor

[Dvali, Shiftman, hep-ph/0001072,Panico, Pomarol, 1603.06609
Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368
Barbieri, 2103.15635]

- Minimally broken $U(2)$ emerges naturally in a **multiscale origin of the flavor hierarchies**:

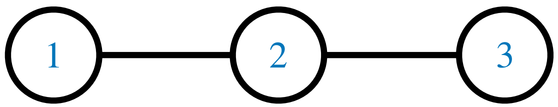


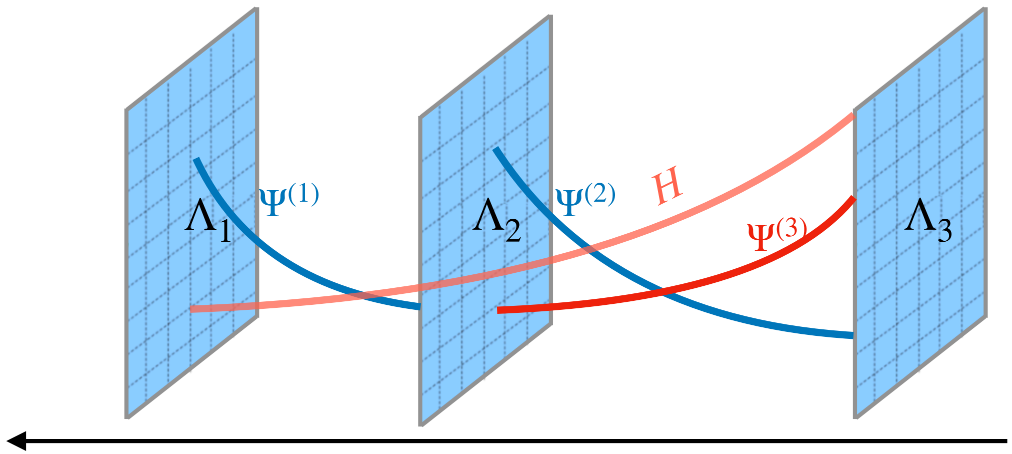
Gauge deconstruction

Composite dynamics

dual

Extra-dimensions



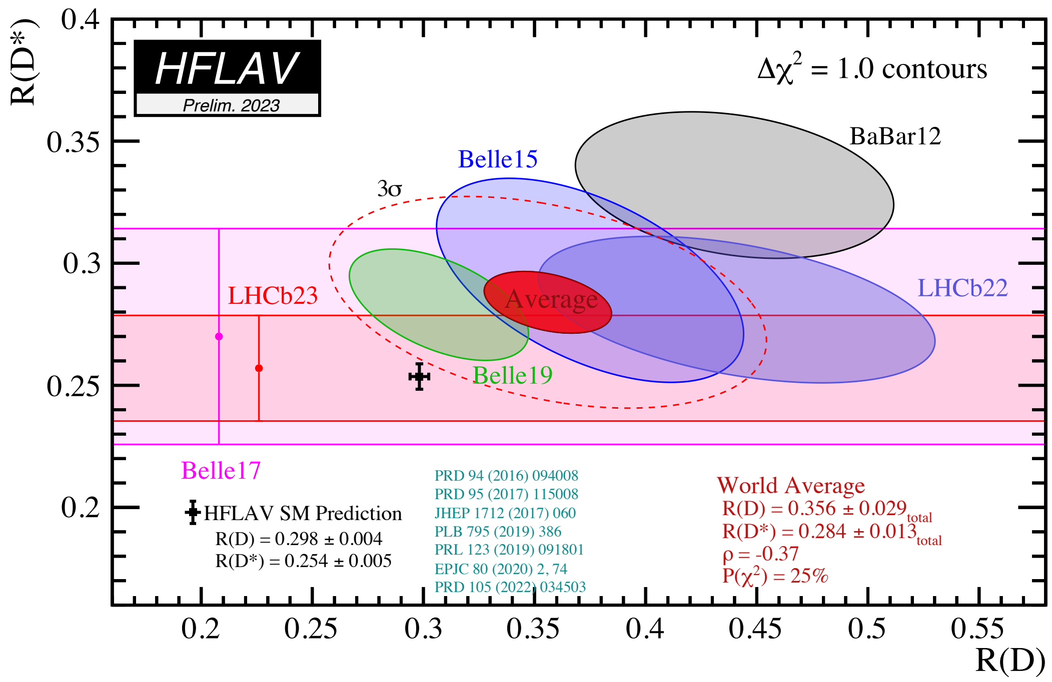


[Panico, Pomarol, 1603.06609; Fuentes-Martin, Isidori, Pages, Stefanek 2012.10492; Fuentes-Martin, Isidori, JML, Selimovic, Stefanek, 2203.01952]

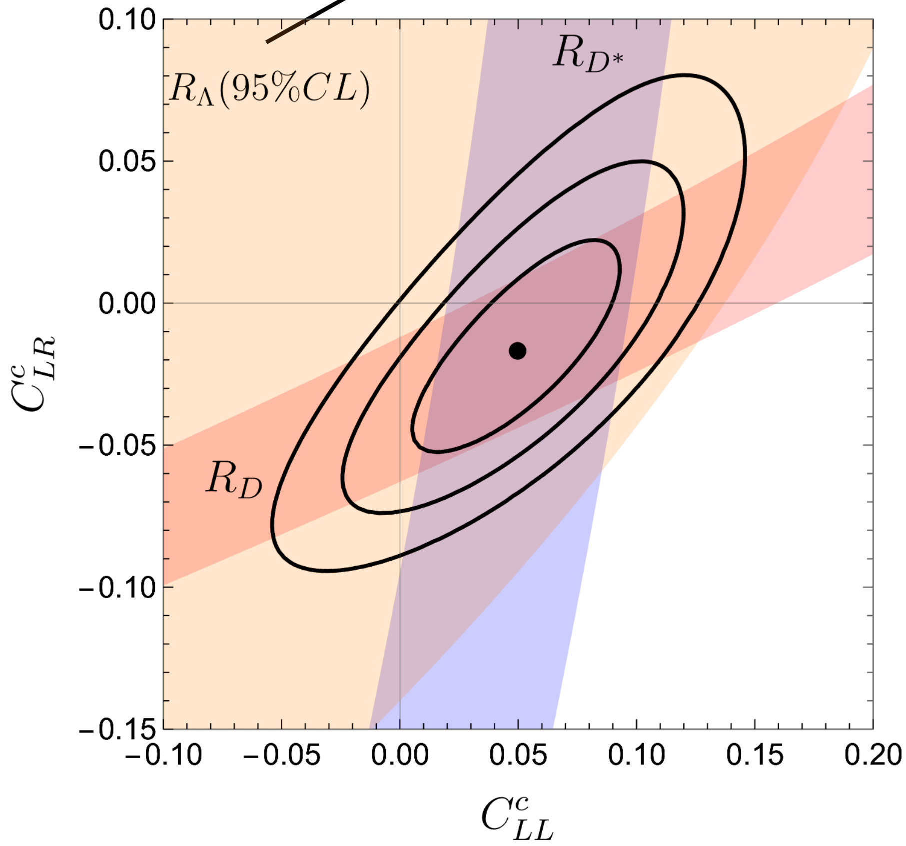
B-anomalies: $R_{D^{(*)}}$

$$\boxed{R_{D^{(*)}} = \frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}l\nu)}}$$

$\sim 3.2\sigma$



$\Lambda_b \to \Lambda_c \tau\nu$



$$\mathscr{L} \supset \frac{2}{v^2} V_{cb} \Big[\big(1 + C^c_{LL}\big)(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_L) - 2 C^c_{LR} (\bar{c}_L b_R)(\bar{\tau}_L \nu_L) \Big]$$

[J. Aebischer, G. Isidori, M. Pesut, B. Stefanek, F. Wilsch, 2210.13422]