Deconstructing flavor anomalously

Javier M. Lizana
IFT Madrid

Based on:
JHEP **07** (2024) 117
2402.09507

(with Javier Fuentes-Martin)

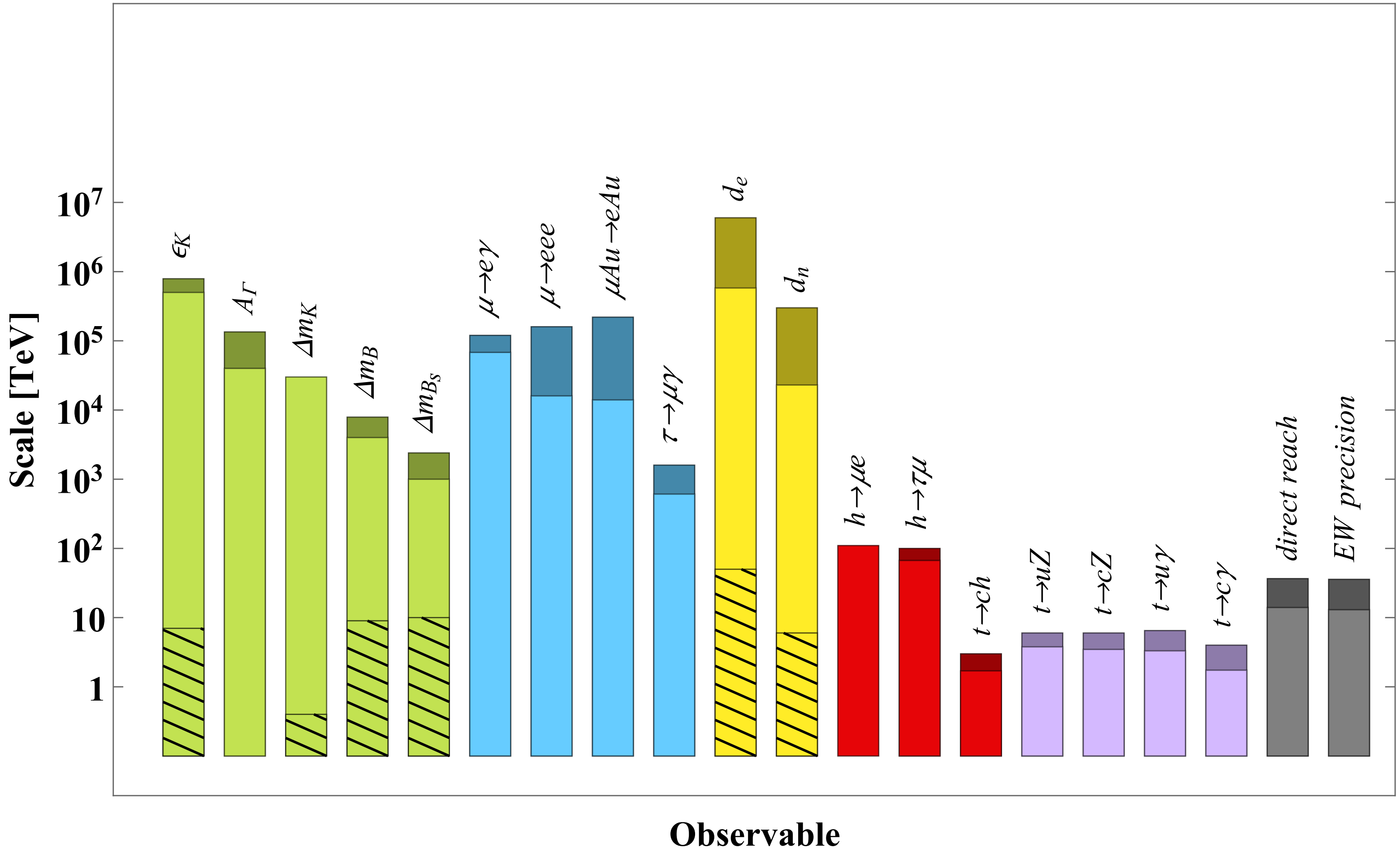
ICHEP 2024, Prague

1

Deconstructing **flavor** anomalously

New Physics bounds

[Physics Briefing Book, 1910.11775]



How to reconcile these strong bounds with NP at the TeV to address the hierarchy problem?

Flavor symmetries of SM

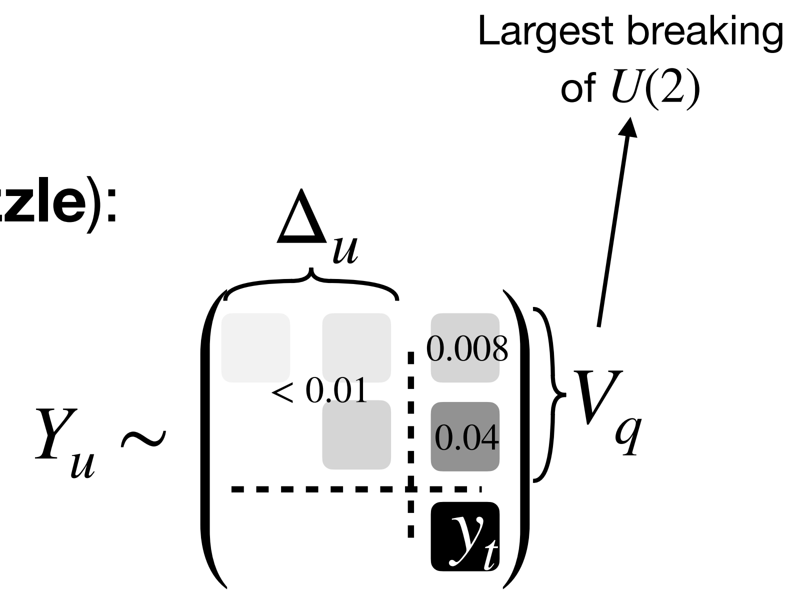
- Flavor symmetry $U(3)^5$, only broken by Yukawas:

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

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

- $Y_{u,d,e}$ very hierarchical (**SM flavor puzzle**):

$$y_t \gg y_{b,\tau} \gg y_{2nd} \gg y_{1st}$$



Flavor symmetries of SM

- To leading order:

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

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

- $V_q \sim 0.04$ (largest breaking of $U(2)$) $\Rightarrow$ Protection in FCNC (GIM)

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

Flavor deconstruction as origin of the flavor hierarchies

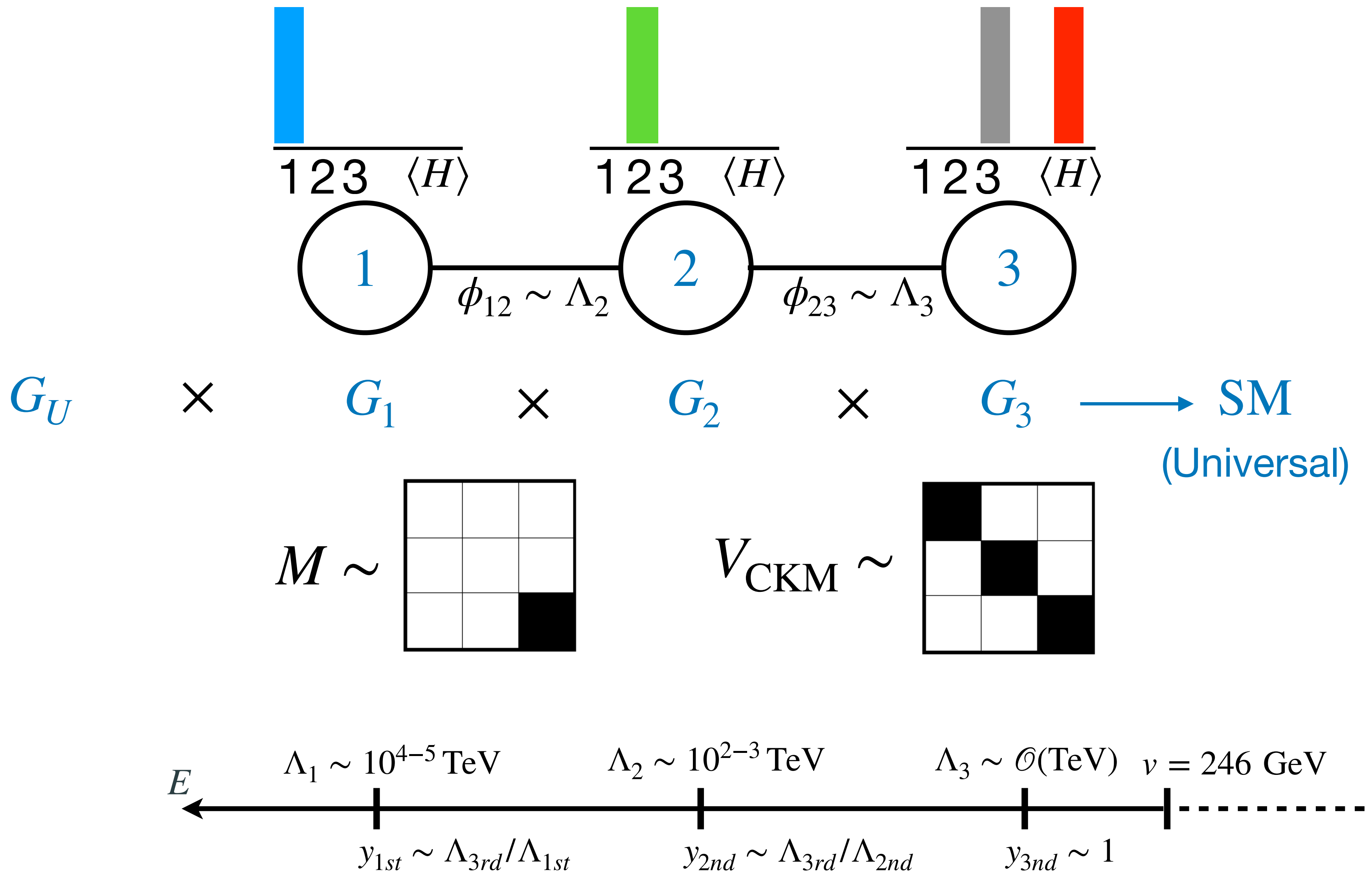
See Allwicher's talk of yesterday

2

Deconstructing flavor anomalously

[Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368, Allwicher, Isidori, Thomsen, 2011.01946]

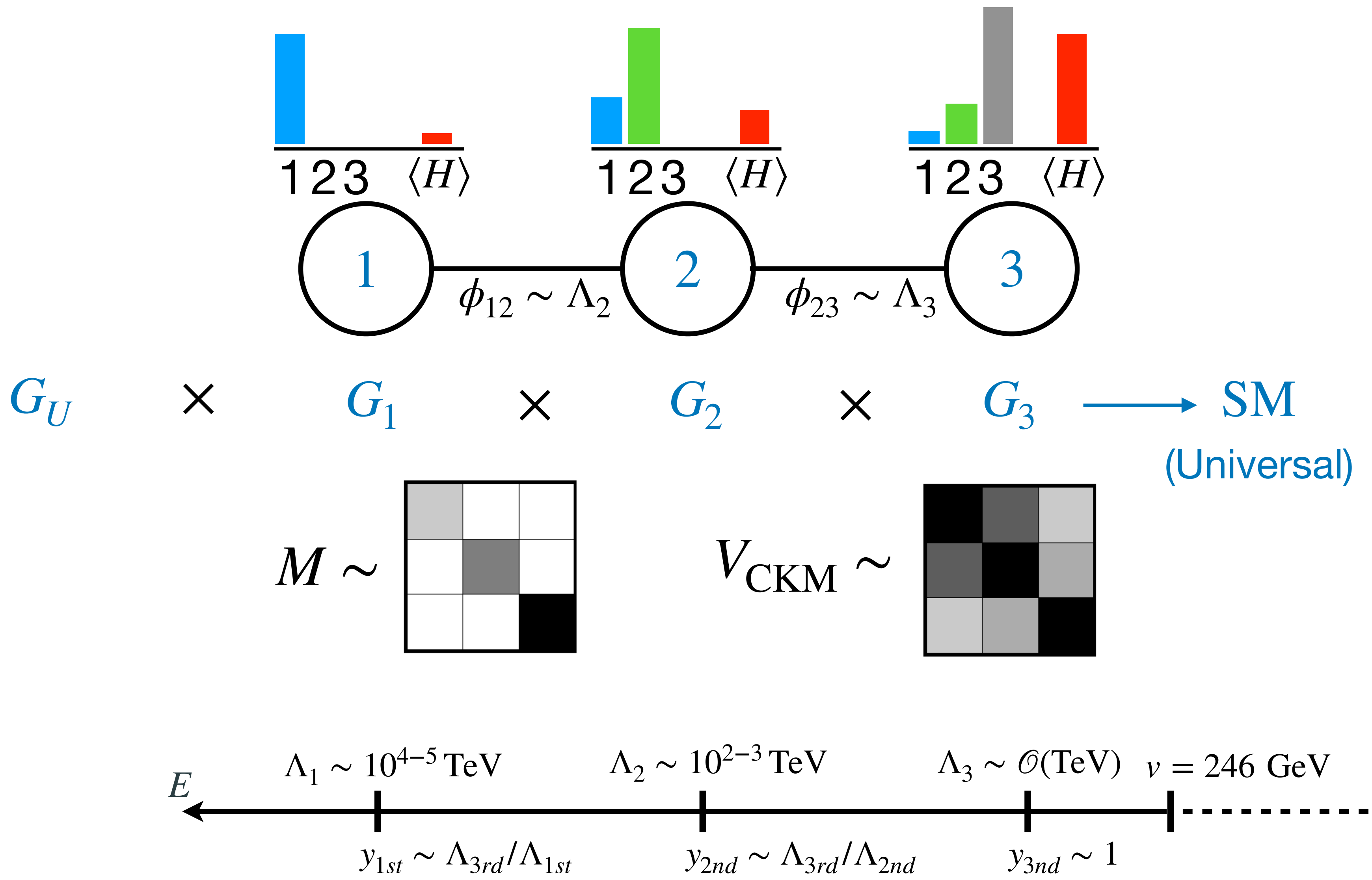
Non-universal gauge extensions



[Berezhiani, Rattazz, hep-ph/9212245; Dvali, Shiftman, hep-ph/0001072; Panico, Pomarol, 1603.06609]

[Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368,
Allwicher, Isidori, Thomsen, 2011.01946]

Non-universal gauge extensions

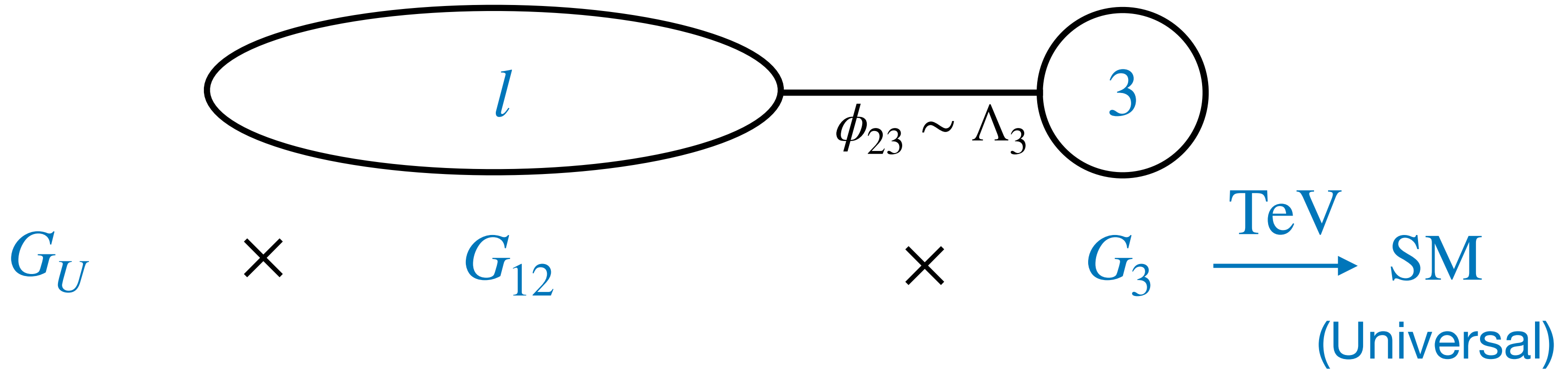


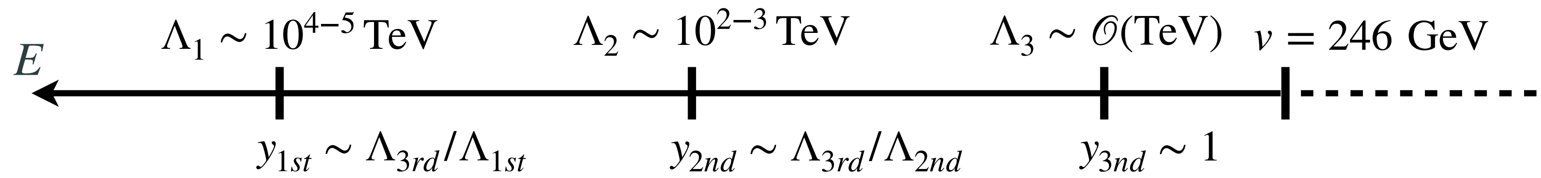
[Berezhiani, Rattazz, hep-ph/9212245; Dvali, Shiftman, hep-ph/0001072; Panico, Pomarol, 1603.06609]

Non-universal gauge extensions

- From the TeV, we see…

Emerging flavor symmetry: $U(2)$





[Berezhiani, Rattazz, hep-ph/9212245; Dvali, Shiftman, hep-ph/0001072; Panico, Pomarol, 1603.06609]

Non-universal gauge extensions

- Examples:

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

$SU(4)_{PS}^h \times SU(3)_c^l \times SU(2)_L \times U(1)_X$ [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]

$SU(4)_{PS}^h \times SU(2)_R^h \times SU(3)_c^l \times U(1)_Y^l \times SU(2)_L$ [Davighi, Isidori, 2303.01520]

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

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

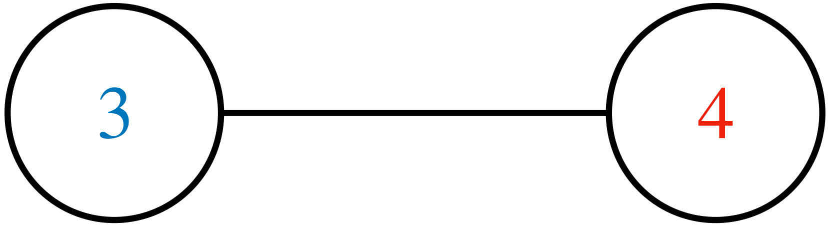
$SU(5) \times SU(5) \times SU(5)$ [Fernández-Navarro, King, Vicente, 2311.05683]

An example to play: 4321

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

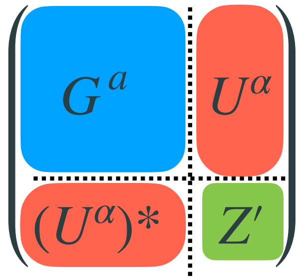
$$SU(4)^h_{PS} \times SU(3)^l_c \times SU(2)_L \times \underbrace{U(1)_X}_{[U(1)_R \times U(1)_{(B-L)^l}]_{\text{diag}}} \rightarrow G_{\text{SM}}$$

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

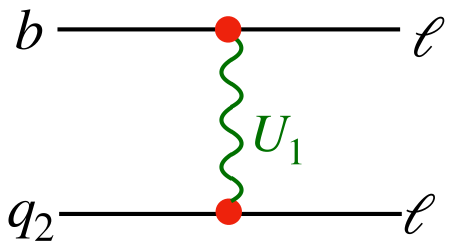


$SU(3)^l_c \times U(1)_{(B-L)^l}$		$SU(4)^h_{PS}$
$q_L^{1,2}$	$\ell_L^{1,2}$	(q_L^3, ℓ_L^3)
$u_R^{1,2}$	$e_R^{1,2}$	(t_R, ν_R)
$d_R^{1,2}$		(b_R, τ_R)

$SU(4)^h_{PS} \sim$

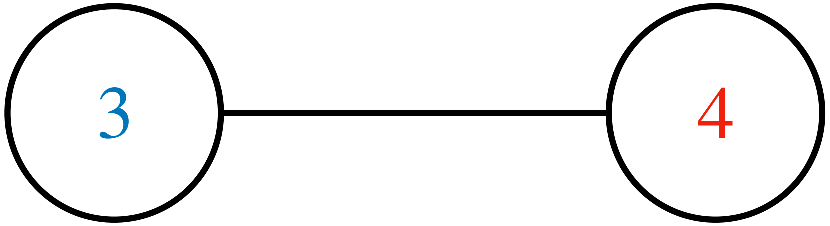


It gives a TeV leptoquark with large couplings to the 3rd family: well studied in the context of B anomalies



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)

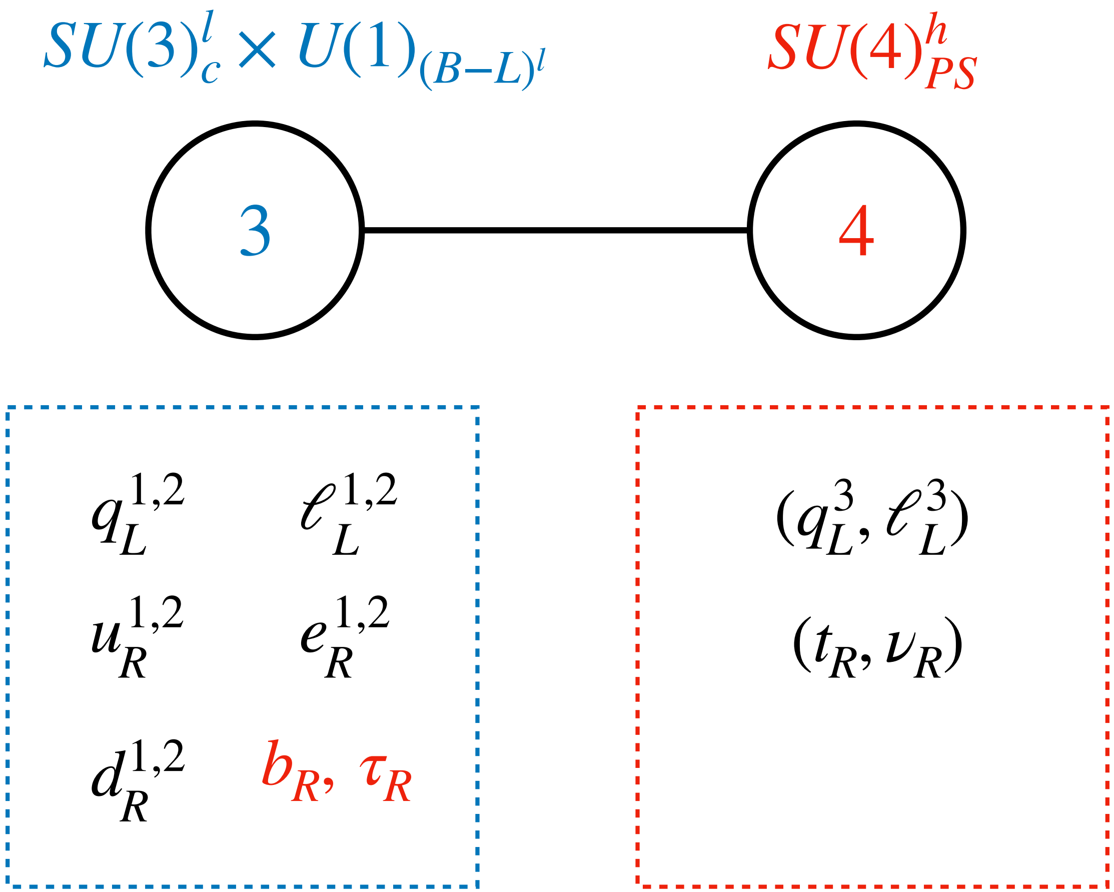
(t_R, ν_R)

(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

Explanation for suppressed CKM mixing

An example to play: 4321



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

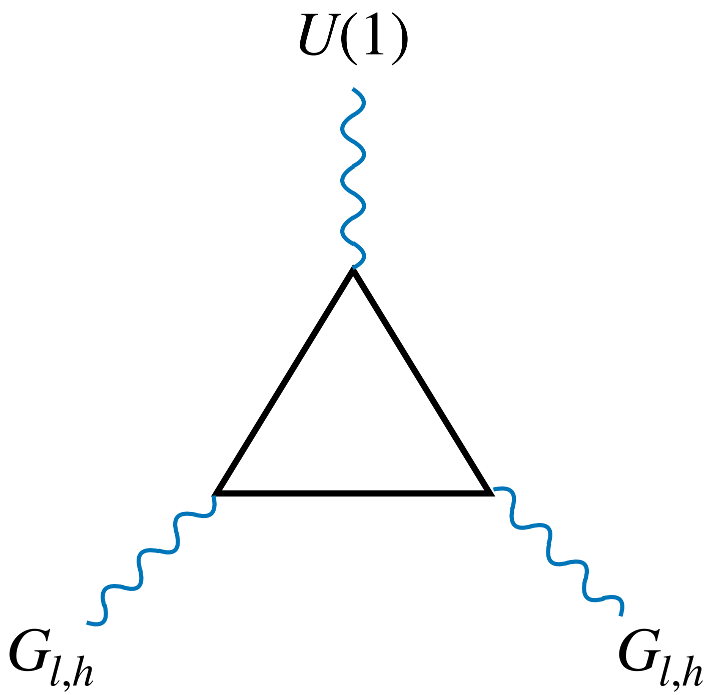
Explanation for suppressed CKM mixing and t-b hierarchy

But…

- Careful with gauge anomalies: **deconstruction family by family**

$$G_h \times G_l \times G_U \longrightarrow G_{\text{SM}}$$

Full families



Otherwise…

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

3

Deconstructing flavor **anomalously**

How to cure gauge anomalies

- Adding Wess-Zumino-Witten terms (it needs to be UV completed).
- 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 ↗

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

… via this sector.

- 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…

$U(1)_Y$ (from $SU(2)_R$ and $U(1)_{B-L}$)

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

$\langle \bar{u}_L u_R + \bar{d}_L d_R \rangle \sim \Lambda f_\pi^2$

	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
(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

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

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: ζ_L, ζ_R

	$SU(N_{\rm HC})$	$SU(4)^h_{PS}$	$SU(4)^l_{PS}$	$U(1)_R$
ζ_L	$\Box$	1	4	
ζ_R	$\Box$	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

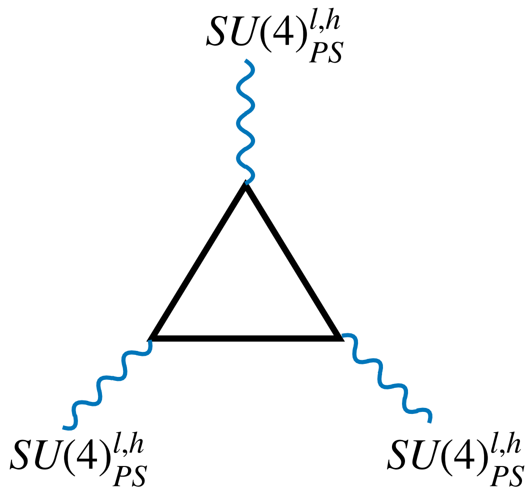
$$SU(4)^h_{PS} \times SU(3)^l_c \times SU(2)_L \times U(1)_X \times SU(N_{\rm HC}) \xrightarrow[\langle \bar{\zeta}_L \zeta_R \rangle \neq 0]{} G_{\rm SM} \times SU(N_{\rm HC})$$

4 hyper-quarks: ζ_L, ζ_R

	$SU(N_{\rm HC})$	$SU(4)^h_{PS}$	$SU(4)^l_{PS}$	$U(1)_R$
ζ_L	$\square$	**1**	**4**	
ζ_R	$\square$	**4**	**1**	
(q_L^3, ℓ_L^3)	**1**	**4**	**1**	0
(t_R, ν_R^3)	**1**	**4**	**1**	1/2
(b_R, τ_R)	**1**	**1**	**4**	-1/2
$(q_L^{1,2}, \ell_l^{1,2})$	**1**	**1**	**4**	0
$(u_R^{1,2}, \nu_R^{1,2})$	**1**	**1**	**4**	1/2
$(d_R^{1,2}, e_R^{1,2})$	**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

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

Cubic anomalies:



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

Realization in 4321

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

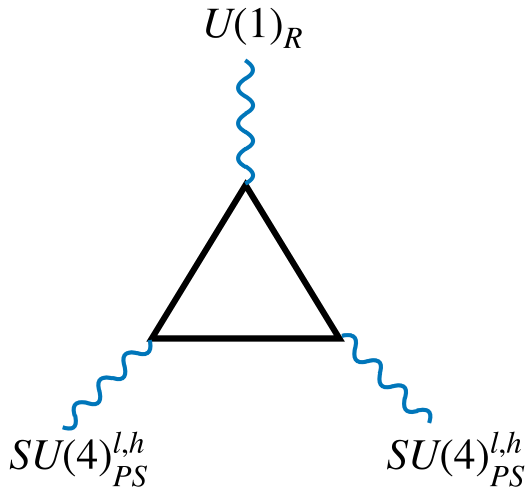
4 hyper-quarks (ζ_L, ζ_R)

	$SU(N_{\rm HC})$	$SU(4)^h_{PS}$	$SU(4)^l_{PS}$	$U(1)_R$
ζ_L	$\square$	**1**	**4**	$-1/2N_{\rm HC}$
ζ_R	$\square$	**4**	**1**	$-1/2N_{\rm HC}$
(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

$$SU(N_{\rm HC}) \times U(1)_{\rm HC} \longrightarrow U(1)_R$$

$$\Lambda > \langle \bar{\zeta}_L \zeta_R \rangle$$

		$SU(N_{\rm HC}+1)$	$SU(4)^h_{PS}$	$SU(4)^l_{PS}$	$SU(2)_R$
	$\Xi_L = (\zeta_L, U_L)$	$\square$	**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**
	$(N_{\rm HC}-1) \times \chi_L$	**1**	**4**	**1**	0
	$(N_{\rm HC}-1) \times \chi_R$	**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:

$$U(2)_q \times U(2)_e$$

[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 $U(1)$ groups.
- 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.

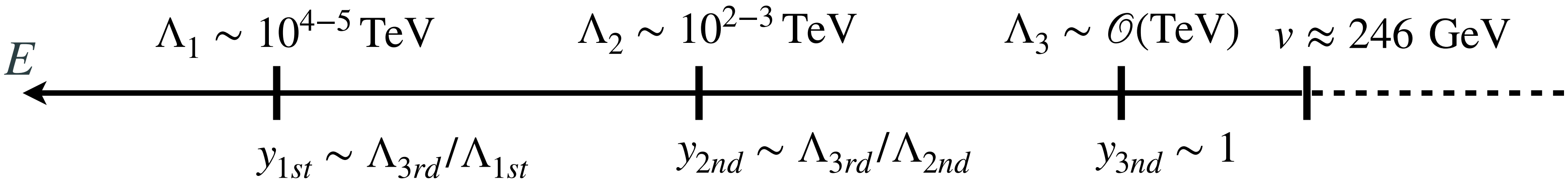
Thank you!

Backup

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**:

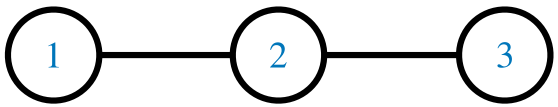


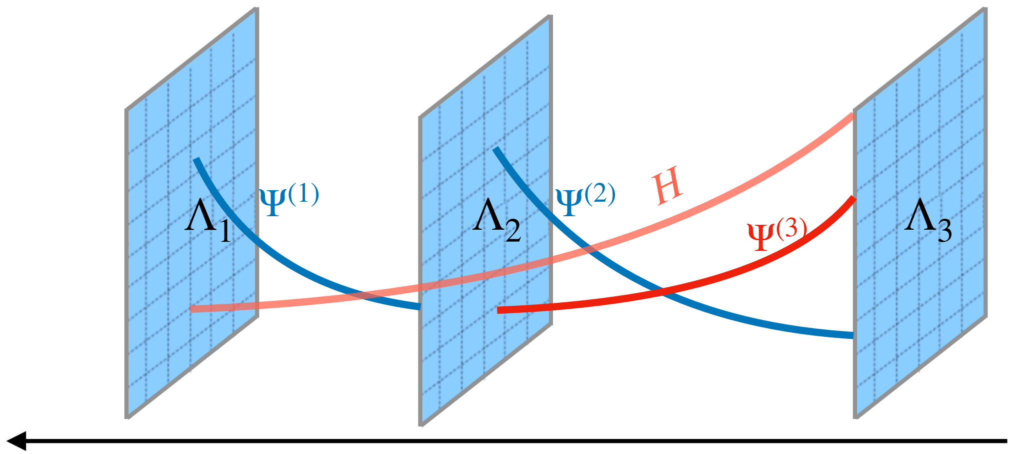
Gauge deconstruction

Composite dynamics

dual

Extra-dimensions





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

[Davighi, Isidori, 2303.01520]

Non-universal gauge extensions

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

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

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

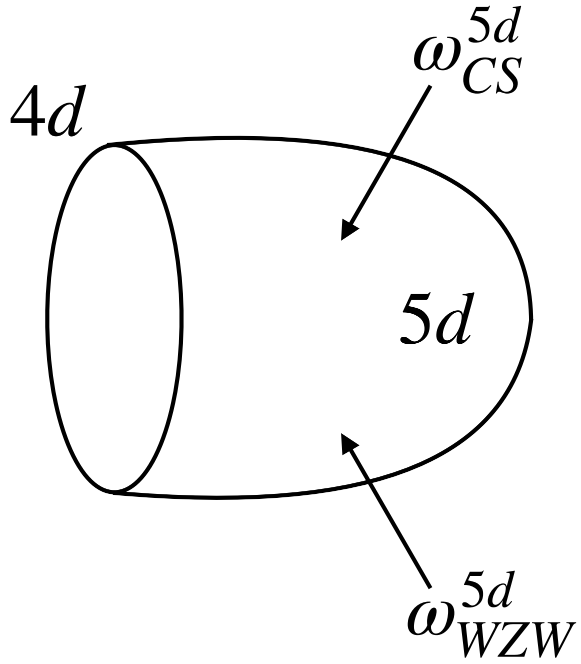
$$SU(2)^l_L \times SU(2)^h_L \times \dots \qquad Y \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}$$

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

- Higher scale NP can generate suppressed extra elements

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]