Third-family quark-lepton unification with a fundamental composite Higgs

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Based on **arXiv:2004.11376** in collaboration with **Peter Stangl**

Mainz Theory Palaver seminar

The SM Lagrangian: Naturalness problems

$$\mathscr{L}_{\text{SM}} = \mathscr{L}_{\text{Gauge}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{Yuk}}$$

3+1 parameters
(flavor universal)

[Strong CP problem]

2 parameters

[Hierarchy problem]

- Experimentally well tested
- Highly symmetric ($U(3)^5$ flavor symmetry)
- Natural (except for θ_{QCD})

- Experimentally less tested
- Seemingly unnatural

The SM Lagrangian: Flavor puzzle

$$\mathscr{L}_{\text{SM}} = \mathscr{L}_{\text{Gauge}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{Yuk}}$$

3+1 parameters
(flavor universal)

[Strong CP problem]

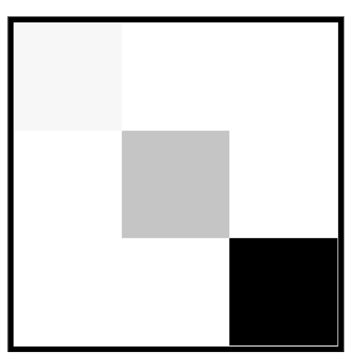
2 parameters

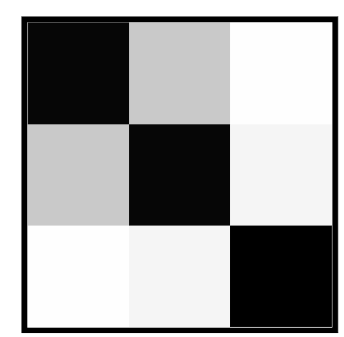
[Hierarchy problem]

Flavor non-universal

The SM Yukawa sector is characterized by 13 parameters (for massless neutrinos)
[3 lepton masses + 6 quark masses + 3+1 CKM parameters]

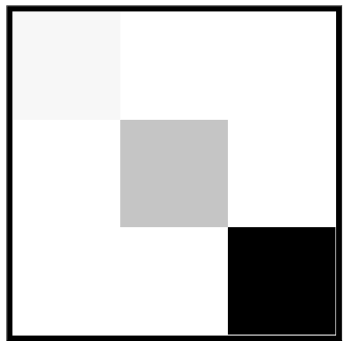
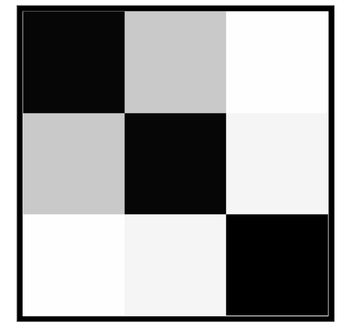
… whose values do not look at all accidental

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

$V_{\text{CKM}} \sim$ 

The $U(2)$ flavor symmetry

The SM Yukawas do not look at all accidental

$M_{u,d,e} \sim$  $V_{\rm CKM} \sim$  $\psi = ((\psi_1\ \psi_2)(\psi_3))$

Hints of underlying (flavor) symmetries?

They respect an approximate $U(2)^5 \equiv U(2)_q \times U(2)_\ell \times U(2)_u \times U(2)_d \times U(2)_e$ symmetry, minimally broken by 5 spurions [Barbieri et al. 1105.2296]

$$Y_{u(d)} = y_{t(b)} \begin{pmatrix} \Delta_{u(d)} & x_{t(b)} V_q \\ 0 & 1 \end{pmatrix} \qquad Y_e = y_\tau \begin{pmatrix} \Delta_e & x_\tau V_\ell \\ 0 & 1 \end{pmatrix}$$

$$|V_q| \sim V_{cb} \qquad |\Delta_u| \sim y_c$$

If NP preserve this symmetry: large NP effects in 3rd generation, gradually smaller effects in the lighter generations

The SM Lagrangian: NP opportunities

$$\mathscr{L}_{\text{SM}} = \mathscr{L}_{\text{Gauge}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{Yuk}}$$

3+1 parameters
(flavor universal)

[Strong CP problem]

2 parameters

[Hierarchy problem]

13 parameters
(flavor non-universal)

[Flavor puzzle]

Hints of underlying symmetries/dynamics?

Strong CP problem: PQ symmetry (axions)? PQ breaking scale should be high

Hierarchy problem: TeV scale NP (flavor structure is needed to avoid constraints)

Flavor puzzle: Flavor symmetries, e.g. $U(2)^5$
(NP coupling dominantly to the third generation, but at which scale?)

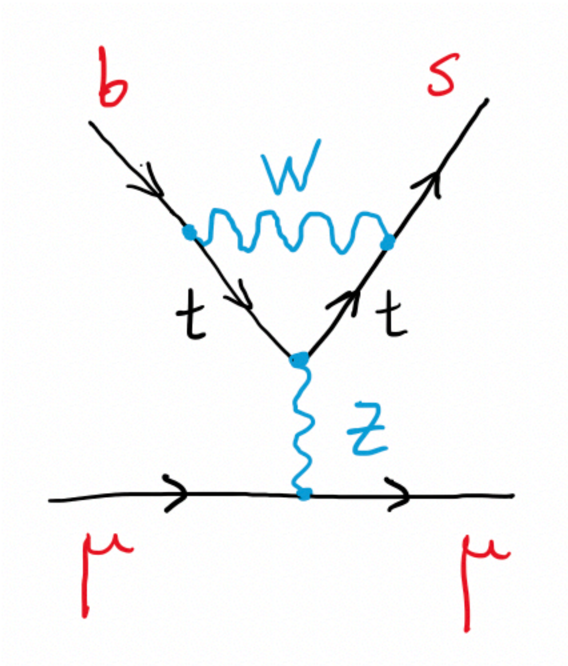
Both related to the Higgs, are these hints connected?

The B anomalies

Hints of Lepton Flavour Universality Violation in semileptonic B decays

$b \to s\ell^+\ell^-$

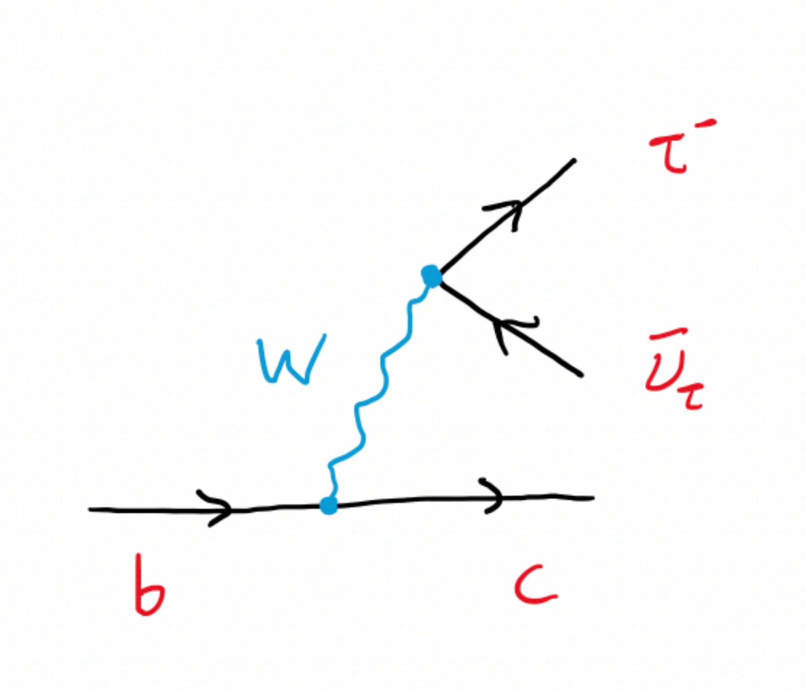
μ/e ~~universality~~



$> 4\,\sigma$

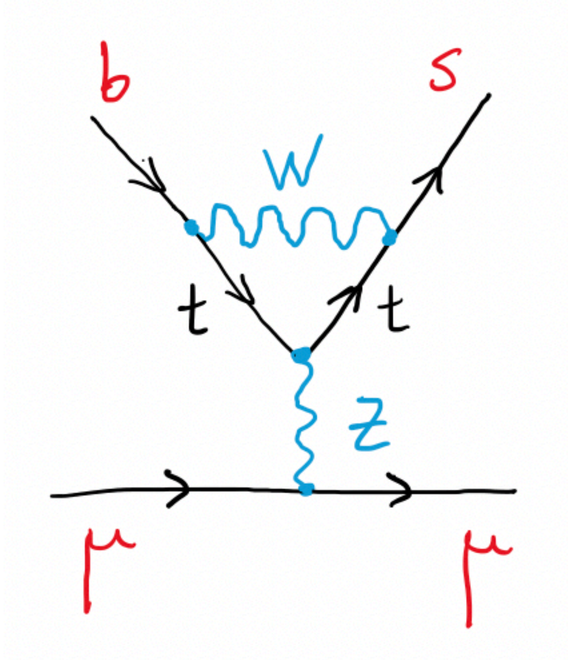
$b \to c\tau\nu$

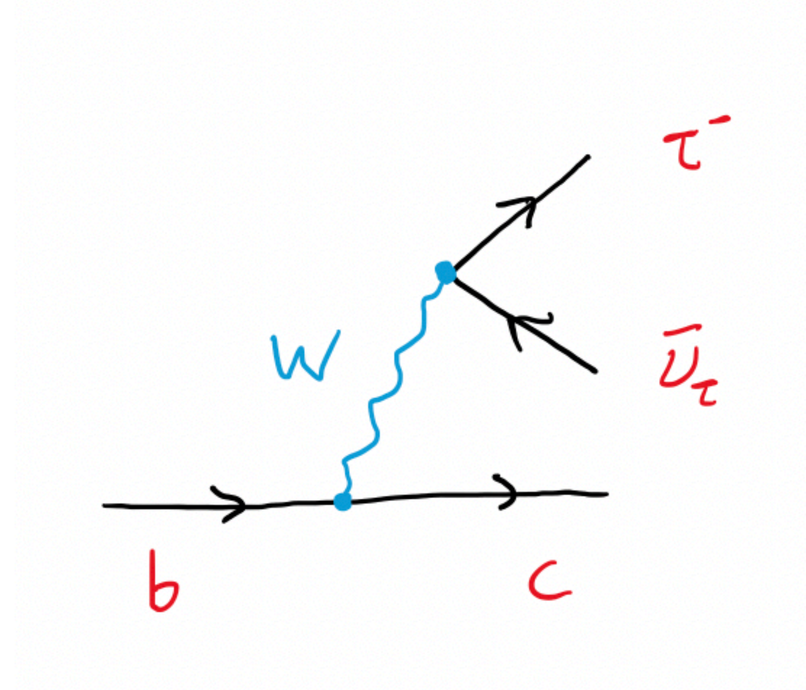
$\tau/\mu\,,e$ ~~universality~~



$\sim 3\,\sigma$

Flavor pattern of the B anomalies





$3_Q \to 2_Q 2_L 2_L$ $\ll$ $3_Q \to 2_Q 3_L 3_L$

~20% of a SM loop effect

~15% of a SM tree-level effect

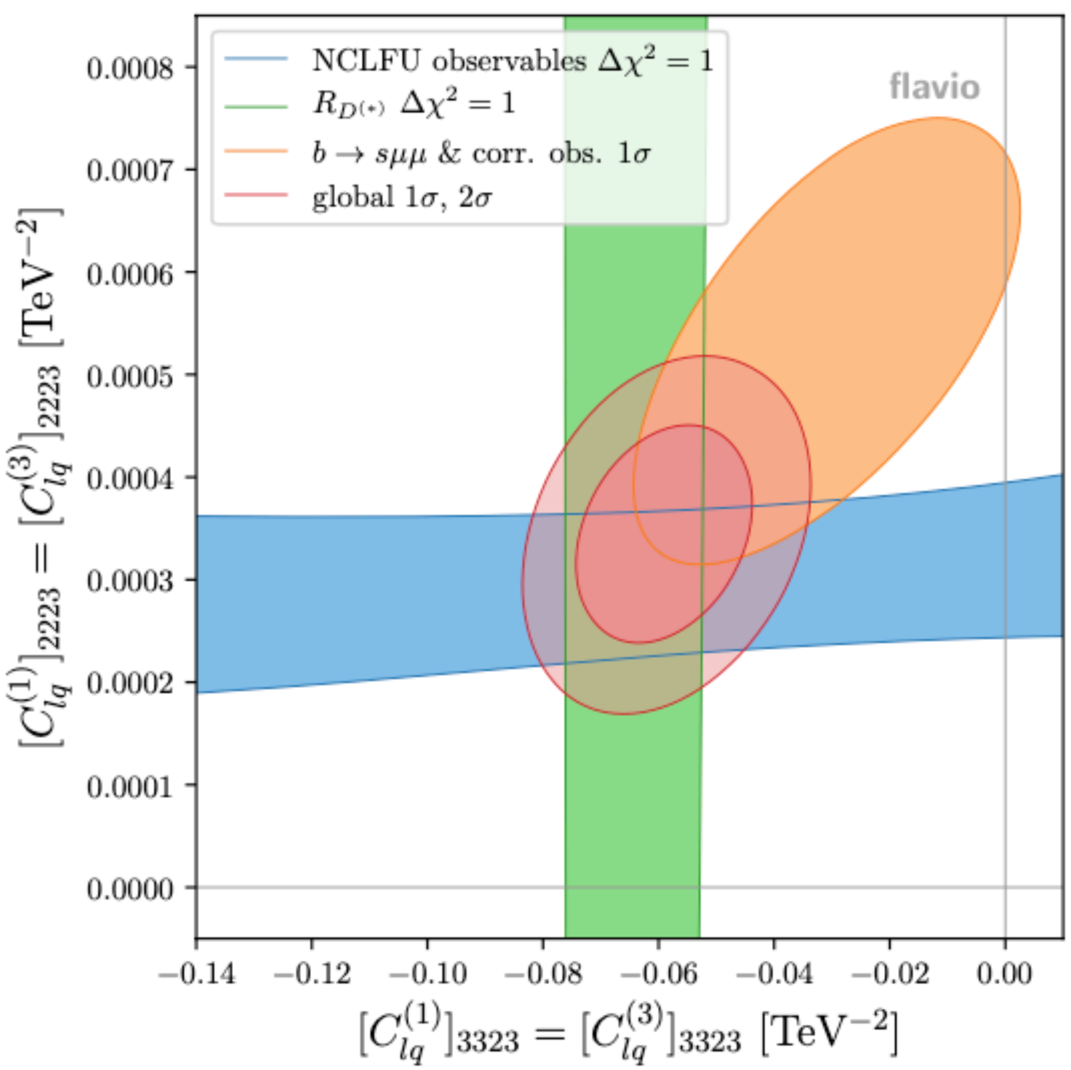
The only source of lepton flavor universality violation in the SM (Yukawas) follows a similar trend: $y_e \ll y_\mu \ll y_\tau \ldots$

TeV-scale NP explanation consistent with $U(2)^5$ flavor symmetry with $|V_{q,\ell}| \sim 0.1$ (roughly the size inferred from the SM Yukawa $|V_q| \sim V_{cb} \approx 0.04$)

[JFM, Isidori, Pagès, Yamamoto, 1909.02519]

Global fits to the anomalies: combined explanation

[Bobeth, Haisch, arXiv:1109.1826; Crivellin et al., arXiv:1807.02068]



[Aebischer et al., arXiv:1903.10434
See also Algueró et al., arXiv:1903.09578]

- **SMEFT operators**

$$O_{lq}^{(1)} = (\bar{l}_L \gamma^\mu l_L)(\bar{q}_L \gamma_\mu q_L)$$

$$O_{lq}^{(3)} = (\bar{l}_L \tau^I \gamma^\mu l_L)(\bar{q}_L \gamma_\mu \tau^I q_L)$$

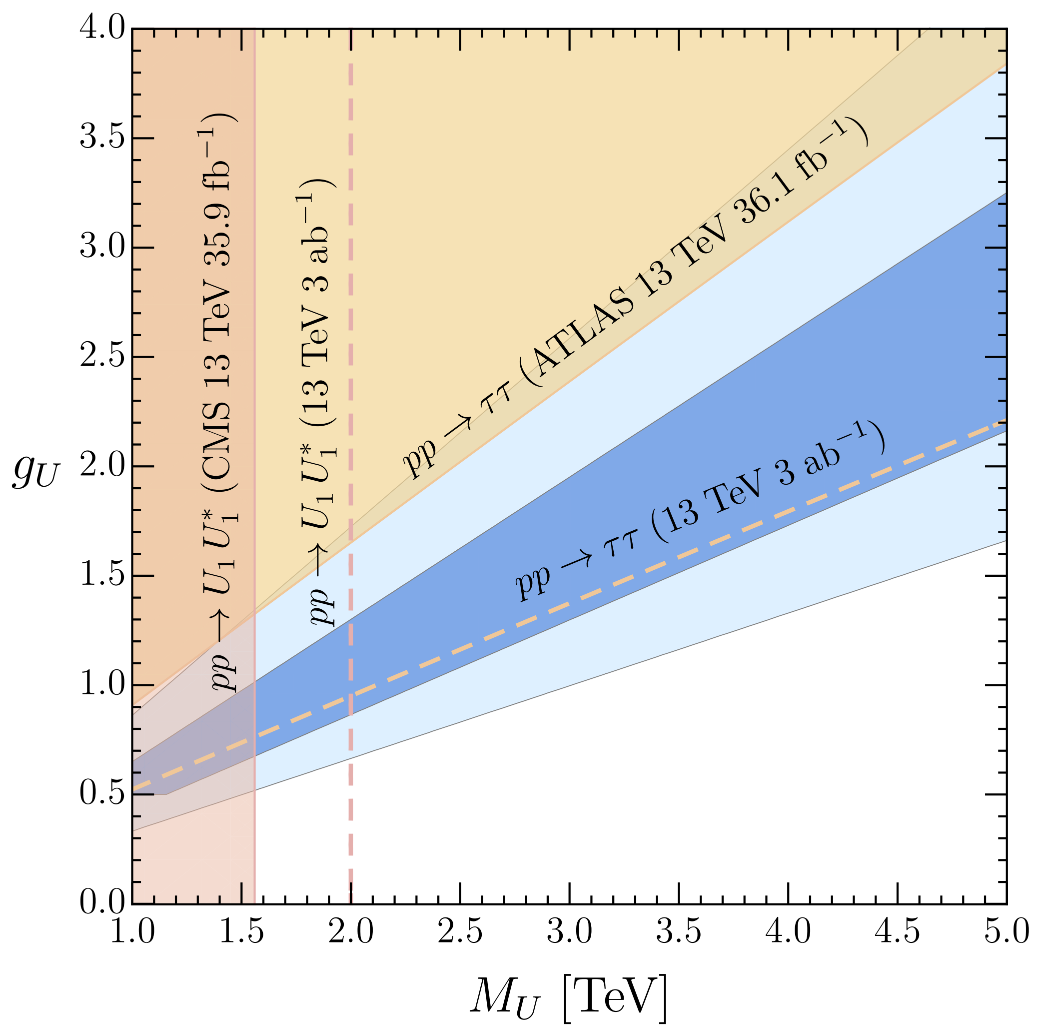
- Constraints from $B \to K^{(*)}\nu\nu$ require $[C_{\ell q}^{(1)}]_{3323} \approx [C_{\ell q}^{(3)}]_{3323}$

- **NP scale** (from $[C_{lq}^{(1)}]_{3323}$): $\Lambda = \dfrac{M_{\rm NP}}{g_{\rm NP}} \sim 4$ TeV

Simplified U_1 leptoquark explanation

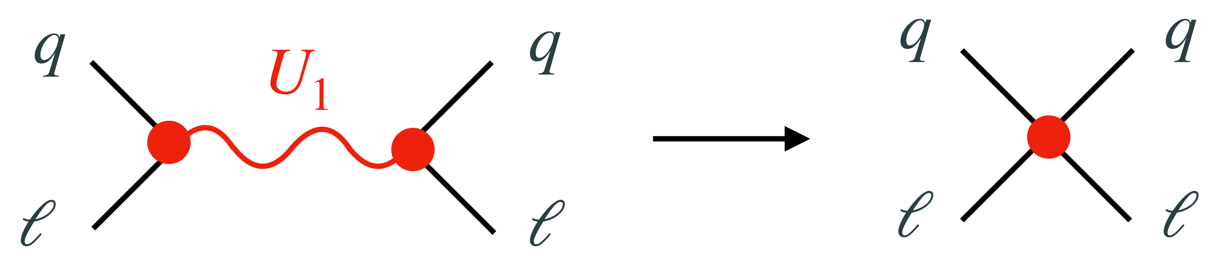
$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta_{i\alpha}^L (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) + \beta_{i\alpha}^R (\bar{d}_R^i \gamma_\mu e_R^\alpha)\right] + \mathrm{h.c.} \qquad U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$$

- Consistent with other low-energy and high-pT data



[Cornella, JFM, Isidori, 1903.11517;
Baker, JFM, Isidori, König, 1901.10480]

- No hadronic and leptonic operators at tree level (strongly constrained by data)



- The required relation $[C_{\ell q}^{(1)}]_{3323} \approx [C_{\ell q}^{(3)}]_{3323}$ is a (tree-level) prediction of the model

- Why not stop here? A massive vector boson requires a **UV completion**

UV completion for the U_1 leptoquark

Massive spin-1 particle → Composite resonance from strong dynamics $\sim \rho_\mu$

Massive spin-1 particle → Gauge boson $\sim W_\mu$ → π_L composite [more later]

Gauge boson $\sim W_\mu$ → π_L fundamental

In all cases, the closure of the algebra of the U_1 generators ($T_\pm$) requires extra states (at least a Z')

[Baker, JFM, Isidori, König, 1901.10480]

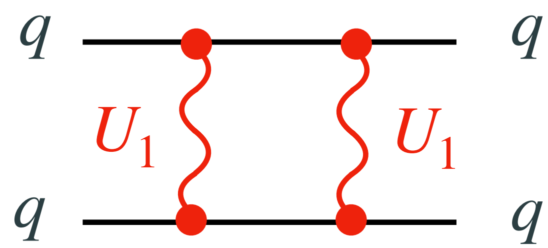
$$\frac{1}{3}\sum_{\alpha,\beta=1}^{3}[T_+^\alpha, T_-^\beta] = T_{B-L}$$

U_1 as a composite resonance:

[Barbieri et al. 1512.01560; Barbieri, Murphy, Senia 1611.04930; Barbieri, Tesi, 1712.06844]

✓ **Hierarchy problem:** Higgs could arise as a pNGB of the strong dynamics

✗ **Non-renormalizable:** Important loop effects can only be guessed by NDA



$$\mathcal{A}_{\Delta F=2} \propto \frac{g_U^4}{M_U^4}\frac{\Lambda^2}{16\pi^2}$$

Gauge UV completion for the U_1 leptoquark

The U_1 solution points to Pati-Salam unification

$$\mathbf{PS} \supset SU(4) \times SU(2)_L \times U(1)_R$$

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

$$SU(4) \sim \left(\begin{array}{c:c} G^a & U^\alpha \\ \hdashline (U^\alpha)^* & Z' \end{array}\right) \qquad \Psi_{L,R} = \begin{pmatrix} Q^1_{L,R} \\ Q^2_{L,R} \\ Q^3_{L,R} \\ L_{L,R} \end{pmatrix}$$

- ✔ $\mathrm{SU}(4)$ is the smallest group containing the $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$
- ✔ No proton decay (protected by symmetry)
- ✘ The (flavor universal) Pati-Salam model cannot work
  - ⟶ The bounds from $K_L \to \mu e$ lift the LQ mass to 100 TeV
- ✘ The associated Z' would be excessively produced at LHC
  - ⟶ $M_U \sim M_{Z'} \sim \mathcal{O}(\mathrm{TeV})$ & $\mathcal{O}(g_s)$ Z' couplings to valence quarks

4321 model(s)

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

$$SU(3)_c \times U(1)_Y = [SU(4) \times SU(3) \times U(1)_X]_{\rm diag}$$

$U(1)_Y$

$$\underset{g_4}{SU(4)} \times \underset{g_3}{SU(3)'} \times SU(2)_L \times \underset{g_1}{U(1)_X} \xrightarrow{SSB} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$+U_1, G', Z'$$

$SU(3)_c$

Why an additional $SU(3)$?

~ The extra $SU(3)$ gives a G' (color-octet), apart from the unavoidable Z'

✔ It decorrelates $SU(4)$ from the SM color group. In the limit $g_4 \gg g_{3,1}$

→ $\mathcal{O}(g_3/g_4)$ and $\mathcal{O}(g_1/g_4)$ G' and Z' couplings to valence quarks (sufficient to pass high-p_T bounds)

Third-family quark-lepton unification at the TeV scale

$U(1)_Y$

$$SU(4)_3 \times SU(3)_{1+2} \times SU(2)_L \times U(1)_X \xrightarrow{\langle \Omega_{1,3,15} \rangle \sim \mathcal{O}(\text{TeV})} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$+ U_1, G', Z'$$

$SU(3)_c$

$$\psi = (\psi_1 \; \psi_2 \; \psi_3)$$

★ Accidental $U(2)^5$ symmetry in gauge sector [direct U_1 couplings to 3rd gen. only]

★ $U(2)^5$ broken by the mixing with χ [source of $V_{q,\ell}$ spurion: U_1 couplings + CKM]

★ Fully calculable

- Vector Leptoquarks Beyond Tree Level
  [JFM, Isidori, König, Selimovic, 1910.13474]
- Vector Leptoquarks Beyond Tree Level II: $\mathcal{O}(\alpha_s)$ Corrections and Radial Modes
  [JFM, Isidori, König, Selimovic, 2006.16250]
- Vector Leptoquarks Beyond Tree Level III: Vector-like Fermions and Flavor Changing Transitions
  [JFM, Isidori, König, Selimovic, 2009.11296]

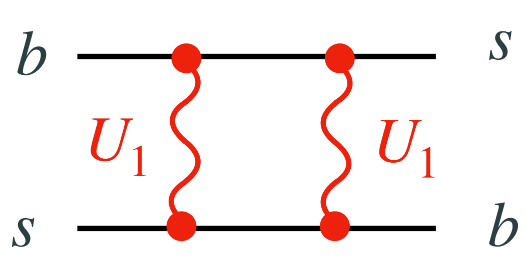
Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$	
q_L^i	**1**	**3**	**2**	$1/6$	1st & 2nd families
u_R^i	**1**	**3**	**1**	$2/3$	
d_R^i	**1**	**3**	**1**	$-1/3$	
ℓ_L^i	**1**	**1**	**2**	$-1/2$	
e_R^i	**1**	**1**	**1**	-1	
ψ_L	**4**	**1**	**2**	0	3rd family
$\psi_R^\pm$	**4**	**1**	**1**	$\pm 1/2$	
χ_L^i	**4**	**1**	**2**	0	$n_{\text{VL}} \geq 2$
χ_R^i	**4**	**1**	**2**	0	
H	**1**	**1**	**2**	$1/2$	
Ω_1	$\bar{\mathbf{4}}$	**1**	**1**	$-1/2$	
Ω_3	$\bar{\mathbf{4}}$	**3**	**1**	$1/6$	
Ω_{15}	**15**	**1**	**1**	0	

[Bordone, Cornella, JFM, Isidori 1712.01368, 1805.09328; Greljo, Stefanek, 1802.04274 (neutrino masses via ISS); Cornella, JFM, Isidori 1903.11517]

Third-family quark-lepton unification at the TeV scale

★ **Fully calculable:** Important effects appear only at one loop

I. bound on M_χ from $\Delta F = 2$
(similar to SM with charm quark)

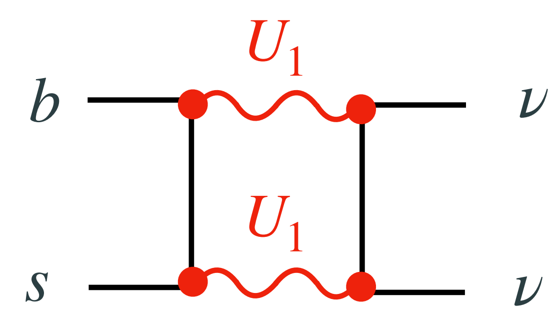


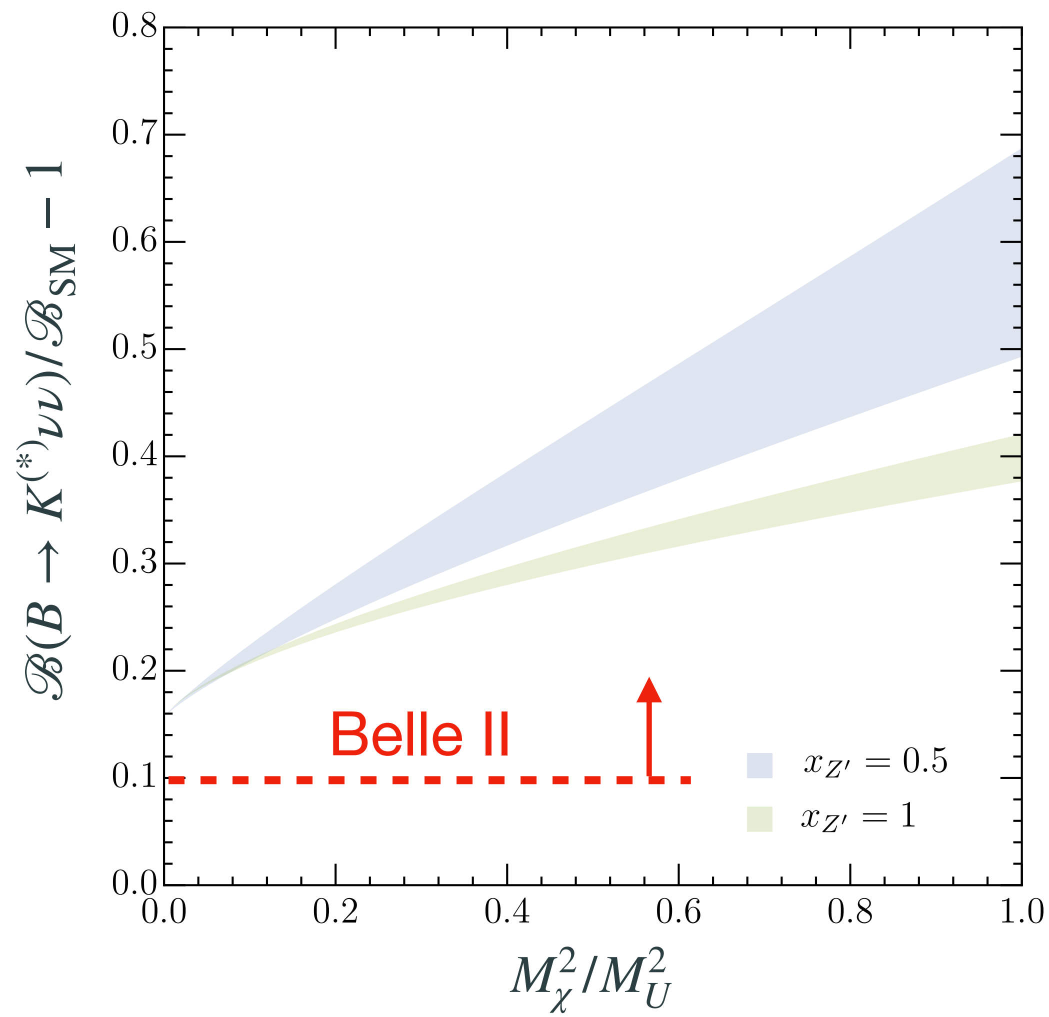
$$\sim \Delta R_{D*}^2 M_\chi^2 \Rightarrow M_\chi \lesssim \mathcal{O}(\text{TeV})$$

[GIM-like suppression of FCNC loops]

[di Luzio, JFM, Greljo, Nardecchia, Renner 1808.00942;
Cornella, JFM, Isidori 1903.11517;
JFM, Isidori, König, Selimovic, 2009.11296]

II. $B \to K^{(*)}\nu\nu$ [JFM, Isidori, König, Selimovic, 2009.11296]





Dynamical 4321 breaking with a composite Higgs

[JFM, Stangl, 2004.11376]

NP scale hinted by the B anomalies suggests a relation to the **SM hierarchy problem**

$U(2)^5$ **flavor symmetry** could **protect a composite Higgs** sector from flavor constraints

Idea

- 4321 symmetry broken by the condensate of new strong dynamics (à la technicolor)
- The same strong dynamics yields a composite pNGB Higgs

A tale in three parts:

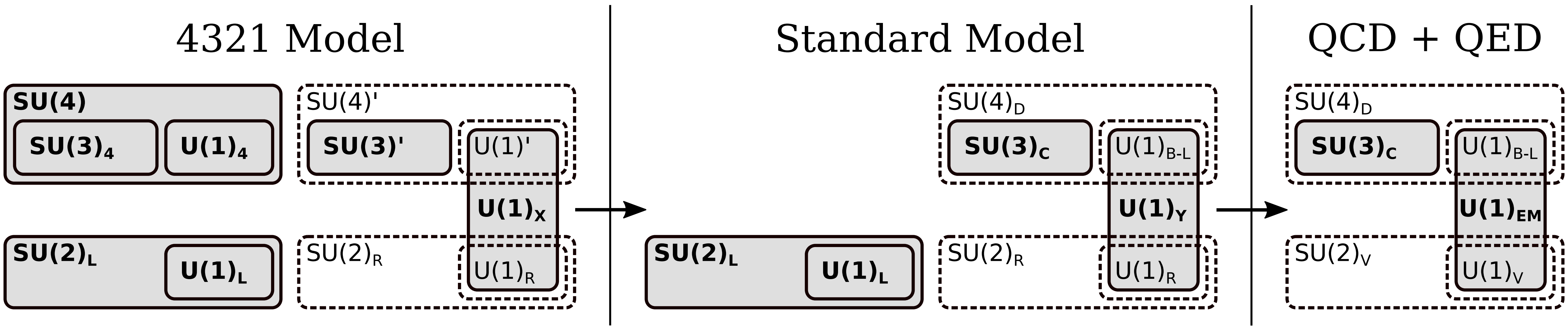
I. A different look at 4321 models

II. Technicolored 4321

III. Composite Higgs sector

4321 symmetry vs EW sector

There is an astonishing similarity between 4321 and EW sectors



	Massive	Massless
Charged (fund.)	$U^{\alpha\pm}$	—
Neutral/Adjoint	Z', G'	B, G

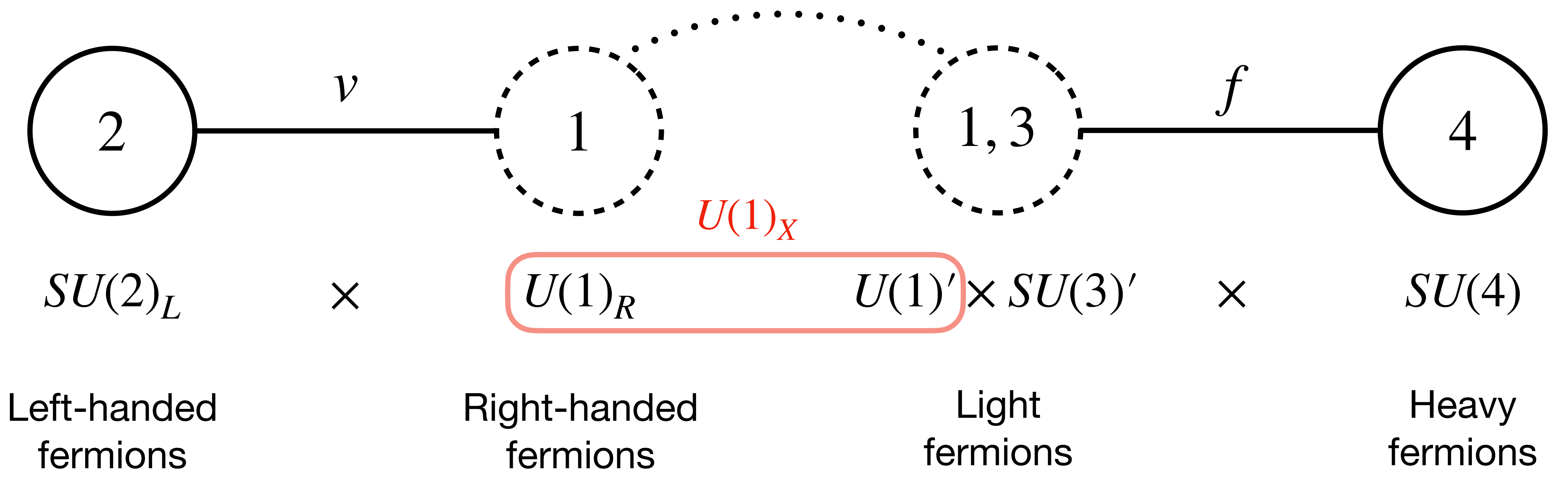
	Massive	Massless
Charged	$W^{\pm}$	—
Neutral	Z	γ

(*) N.B.: Dashed boxes are global symmetries in the limit of vanishing gauge and Yukawa couplings

4321 models as two 2-site models

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

$U(1)_X \equiv [U(1)_R \times U(1)']_{\rm diag}$



There are two separate custodial symmetries:

$SU(2)_C \equiv [SU(2)_L \times SU(2)_R]_{\rm diag}$

$SU(4)_C \equiv [SU(4) \times SU(4)']_{\rm diag}$

Dynamical symmetry breaking: minimal technicolor

- QCD with $N_f = 2$ quark flavors has the global (chiral) symmetry

$$\mathcal{G}_{\text{Global}} \equiv SU(2)_L \times SU(2)_R$$

Field	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$
$q_L = (u_L\, d_L)^\intercal$	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{1}$
$q_R = (u_R\, d_R)^\intercal$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{2}$

- The quark condensate $\langle \bar{q}_L^i\, q_R^j \rangle \approx -4\pi f_\pi^3\, \delta_{ij}$ only invariant under $SU(2)_{L+R}$

$$SU(2)_L \times SU(2)_R \xrightarrow{\langle \bar{q}_L^i\, q_R^j \rangle} SU(2)_{L+R}$$

yielding EWSB but at a much lower scale, $f_\pi \approx 92$ MeV vs $v \approx 246$ GeV

Technicolor idea: Take a scaled-up version of 2-flavor QCD, such that $f_{\text{TC}} \approx 246$ GeV

✘ Excluded by EWPD and by the Higgs discovery

[Weinberg, Phys. Rev. D13 (1976) 974–996; Susskind, Phys. Rev. D20 (1979) 2619–2625; Farhi, Susskind, Phys. Rept. 74 (1981) 277]

… but a technicolor-like breaking of the 4321 symmetry still remains possible!

Technicolored 4321: General idea

- Take a QCD-like theory with $N_f = 4$ quark flavors $\zeta_{L,R}$ and identify a subgroup of the global (chiral) symmetry with (part of) 4321

$$\mathcal{G}_{\text{Global}} \equiv SU(4)_L \times SU(4)_R$$

Field	$SU(N)_{\text{HC}}$	$SU(4)_L$	$SU(4)_R$
ζ_L	$\square$	**4**	**1**
ζ_R	$\square$	**1**	**4**

Gauge symmetry:

$SU(4)_L \supset SU(3)' \times U(1)'$, with $SU(3)'$ and (part of) $U(1)'$ being the ones of 4321

$SU(4)_R$ is identified with $SU(4)$ in 4321

- The hyper-quark condensate $\langle \bar{\zeta}_L^\alpha \, \zeta_R^\beta \rangle \approx -4\pi f_\zeta^3 \, \delta_{\alpha\beta}$ triggers the symmetry breaking

$$SU(4)_L \times SU(4)_R \to SU(4)_{L+R}$$

yielding 4321 symmetry breaking at a scale $f_\zeta \sim \mathcal{O}(\text{TeV})$. All 15 Goldstones are eaten by the massive gauge bosons

Technicolored 4321: Additional fermions

- The hyper-quarks alone are not enough to cancel gauge anomalies. New fermions are required

Field	$SU(N)_{\rm HC}$	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
ζ_R	$\square$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	0
$\zeta_L^q \oplus \zeta_L^\ell$	$\square$	$\mathbf{1}$	$\mathbf{3}\oplus\mathbf{1}$	$\mathbf{1}$	$1/6 \oplus -1/2$
χ_L^i	$\mathbf{1}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
$\chi_R^{q\,i} \oplus \chi_R^{\ell\,i}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}\oplus\mathbf{1}$	$\mathbf{2}$	$1/6 \oplus -1/2$

→ Analog to SM leptons

Fixed by anomaly cancellation ($SU(4)$, $SU(3)'$)

There is freedom (multiplicity fixed) ($SU(2)_L$, $U(1)_X$)

$n_\chi = N/2$

- χ are vector-like under the SM subgroup. We can give them a mass like in technicolor

$$\mathscr{L} \supset \frac{c_\chi^{q,\ell}}{\Lambda_{\rm EHC}^2}(\bar\zeta_L^{q,\ell}\zeta_R)(\bar\chi_L\chi_R^{q,\ell}) - M_q(\bar q_L\chi_R^q) - M_\ell(\bar\ell_L\chi_R^\ell)$$

~~$U(2)^5$~~

$$M_\chi = c_\chi^{q,\ell}\frac{4\pi f_\zeta^3}{\Lambda_{\rm EHC}^2} \sim \mathcal{O}(\text{TeV}) \qquad [\Lambda_{\rm EHC}\sim\mathcal{O}(10\ \text{TeV})]$$

χ play the same role of the vector-like fermions in the fundamental 4321!

- If $M_\chi \gg M_{q,\ell}$ the $U(2)^5$ flavor symmetry is approximately preserved (fit to CKM structure)

$$\frac{1}{\Lambda_{\rm EHC}^2}(\bar\chi_L\chi_R^{q,\ell})^2$$

Harmless (protected by $U(2)^5$)

Technicolored 4321: Predictions

- Vector-like fermions are connected to the HC sector
  - Multiplicities determined by N (number of hypercolors)
  - Mass connected to the HC condensate

- The technicolored 4321 approximately preserves the $SU(4)_C$ symmetry

$$\rho_1 \equiv \frac{M_U^2}{M_{Z'}^2\, cos^2\,\theta_1} \qquad \rho_3 \equiv \frac{M_U^2}{M_{G'}^2\, cos^2\,\theta_3} \qquad \cos\theta_{1,3} = \frac{g_4}{g_{1,3}}$$

Analogous to the SM ρ parameter. In the limit $g_4 \gg g_{1,3}: M_U \approx M_{Z'} \approx M_{G'} \quad (\rho_{1,3} \approx 1)$

- Absence of 4321-breaking scalar sector and radial Higgs-like states. Instead, new resonances should appear at $m_R \sim 4\pi f_\zeta/\sqrt{N}$

Composite Higgs

- Higgs is not elementary but a bound state of new strong interactions
- Lightness of Higgs compared to NP scale: **Higgs as pseudo-Nambu-Goldstone boson** (pNGB) of a spontaneously broken global symmetry

[Kaplan, Georgi, Phys.Lett. B136 (1984) 183;
Dugan, Georgi, Kaplan, Nucl.Phys. B254 (1985) 299]

Avoiding flavor constraints

- Common approach: Elementary fermions mix with composite fermions, which couple to composite Higgs (**partial compositeness**) [Kaplan, Nucl. Phys. B365 (1991) 259–278]
- However, explicit realizations in terms of baryonic composite fermions seem unable to reproduce Yukawa couplings [DeGrand, Shamir, arXiv:1508.02581; Pica, Sannino, arXiv:1604.02572]
- $U(2)^5$ **flavor symmetry** also protects from constraints when direct composite Higgs couplings to elementary fermions are present

$$\mathcal{H} \equiv \bar{\Psi}\Psi \qquad \frac{1}{\Lambda_{\rm EHC}^2}\,\bar{\psi}_{\rm SM}\psi_{\rm SM}\,\mathcal{H} \longrightarrow \frac{1}{\Lambda_{\rm EHC}^2}\,(\bar{\psi}_{\rm SM}\psi_{\rm SM})^2$$

Minimal fundamental composite Higgs

[see e.g. Cacciapaglia, Sannino, arXiv:1402.0233]

- Take a QCD-like theory with 2 Dirac fermions in the **pseudoreal representation**

Global symmetry $SU(4)$

$\langle \bar{\xi}_L^{i\,c} \xi_L^j \rangle = \langle \bar{\xi}_R^{i\,c} \xi_R^j \rangle \approx 4\pi f_\xi^3\, \epsilon_{ij}$

$Sp(4) \cong SO(5) \supset SU(2)_L \times SU(2)_R$

$+H, \eta_5$ (pNGBs)

$\langle \xi_L^i \xi_R^i \rangle \propto \langle h \rangle\, \delta_{ij}$

(like technicolor vacuum)

One loop vacuum misalignment (Higgs potential)

$SU(2)_{L+R}$

For $f_\xi \approx 2.5$ TeV about 1% tuning needed

$\Xi = (\xi_L^1\ \ \xi_L^2\ \ \xi_R^{1\,c}\ \ \xi_R^{2\,c})$

Field	$SU(N)_{\rm HC}$	$SU(2)_L$	$SU(2)_R$
ξ_L	Pseudoreal	**2**	**1**
ξ_R	Pseudoreal	**1**	**2**

Features:

✳ Custodially preserving (automatic)

✳ Only one extra pNGB η_5 (SM singlet)

✳ No double-tuning: once $\langle h \rangle$ is tuned, no extra tuning needed for the Higgs mass

Fundamental composite Higgs + technicolored 4321

- Confining hypercolor gauge group $SU(6)_{\rm HC}$ has a **pseudoreal** $A_3 = \mathbf{20}$ representation [$SU(N)$ has pseudoreal representations only for $N = 2 + 4\,n$]

Field	$SU(6)_{\rm HC}$	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
χ_L^i	$\mathbf{1}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
$\chi_R^{qi} \oplus \chi_R^{\ell i}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3} \oplus \mathbf{1}$	$\mathbf{2}$	$1/6 \oplus -1/2$
$\zeta_L^q \oplus \zeta_L^\ell$	$\mathbf{6}$	$\mathbf{1}$	$\mathbf{3} \oplus \mathbf{1}$	$\mathbf{1}$	$1/6 \oplus -1/2$
ζ_R	$\mathbf{6}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	0
ξ_L	$\mathbf{20}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	0
$\xi_R^\pm$	$\mathbf{20}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\pm 1/2$

$N = 6$ fixes $n_\chi = 3$
(or $n_\chi = 2$ and $n_{\chi'} = 1$)

- Since ζ and ξ transform under different HC representations, the global symmetry factorizes (except for $U(1)_A$)

$$\underbrace{SU(4)_L \times SU(4)_R}_{\zeta} \times \underbrace{SU(4)}_{\xi} \times U(1)_A \to SU(4)_{L+R} \times Sp(4)$$

New pNGB η_1 (SM singlet)

$U(1)_A \equiv$ Anomaly-free combination of axial symmetries for ζ and ξ

N.B.: An interesting alternative is $N = 4$ and and five $\xi \sim A_2 = \mathbf{6}$ (real), yielding $SU(5) \to SO(5)$

Composite Higgs Yukawa interactions

~~$U(2)^5$~~

E

$\Lambda''_{\rm EHC} \sim \mathcal{O}(100~\text{TeV})$

$$\frac{1}{\Lambda''^2_{\rm EHC}}\Big[y_u\,(\bar q_L u_R)\underbrace{(\bar\xi^+_R\,\xi_L)}_{\tilde H} + y_d\,(\bar q_L d_R)\underbrace{(\bar\xi^-_R\,\xi_L)}_{H} + y_e\,(\bar\ell_L e_R)(\bar\xi^-_R\,\xi_L)\Big]$$

$\Delta_{u,d,e}$ spurions

$\Lambda'_{\rm EHC} \sim \mathcal{O}(50~\text{TeV})$

$$\frac{1}{\Lambda'^2_{\rm EHC}}\Big[c_q\,(\bar q_L \chi^q_R) + c_\ell\,(\bar\ell_L \chi^\ell_R)\Big](\bar\xi^{+\,c}_R\,\xi^-_R)$$

$V_{q,\ell}$ spurions
[Same as $M_{q,\ell}$]

$\Lambda_{\rm EHC} \sim \mathcal{O}(10~\text{TeV})$

$$\frac{1}{\Lambda^2_{\rm EHC}}\Big[y_\psi\,(\bar\psi_L\psi_R) + y_{\chi\psi}(\bar\chi_L\psi_R)\Big]\underbrace{(\bar\xi^+_R\,\xi_L)}_{H}$$

3rd gen Yukawa

2-3 CKM mixing
[after mixing with χ]

$f_{\zeta,\xi} \sim \mathcal{O}(\text{TeV})$

$v \approx 246~\text{GeV}$

- For $y_t \sim \mathcal{O}(1)$ we need $\Lambda_{\rm EHC} \sim \mathcal{O}(10~\text{TeV})$
  [same scale as for χ masses (will-be VL fermions)]
- Other 4F operators **protected** by approximate **$U(2)^5$ flavor symmetry**

Conclusions

I presented an attempt of connecting the 4321 gauge symmetry (third-family quark-lepton unification) to a solution of the hierarchy problem

Fundamental HC sector

Field	$SU(6)_{\rm HC}$	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
q_L^i	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
u_R^i	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$
d_R^i	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
ℓ_L^i	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
e_R^i	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1
ψ_L	$\mathbf{1}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
$\psi_R^\pm$	$\mathbf{1}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$\pm 1/2$
χ_L^j	$\mathbf{1}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
$\chi_R^{qj} \oplus \chi_R^{\ell j}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3} \oplus \mathbf{1}$	$\mathbf{2}$	$1/6 \oplus -1/2$
ζ_R	$\mathbf{6}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	0
$\zeta_L^q \oplus \zeta_L^\ell$	$\mathbf{6}$	$\mathbf{1}$	$\mathbf{3} \oplus \mathbf{1}$	$\mathbf{1}$	$1/6 \oplus -1/2$
ξ_L	$\mathbf{20}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	0
$\xi_R^\pm$	$\mathbf{20}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\pm 1/2$

HC confinement →

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
q_L^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
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	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
$\psi_R^\pm$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$\pm 1/2$
χ_L^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
$\chi_R^{qi} \oplus \chi_R^{\ell i}$	$\mathbf{1}$	$\mathbf{3} \oplus \mathbf{1}$	$\mathbf{2}$	$1/6 \oplus -1/2$
H	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
η_5	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	0
η_1	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	0
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

Features:

- Symmetry breaking from dynamics and hierarchy problem down to 1% tuning
- (Will-be) vector-like fermions "predicted" by anomaly cancellation ($n_{\rm VL} = 3$ for $N = 6$)
- Prediction for the new vector masses $M_U \approx M_{G'} \approx M_{Z'}$

Open questions:

- Dark matter? Chimera baryon $\mathscr{B} \sim (\mathbf{6}\,\mathbf{6}\,\mathbf{6}\,\mathbf{20})$ spectrum contains a SM-singlet of spin 1
- How does the EHC sector looks like?

Thank you!