Common exotic decays of VLQs

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[1803.00021,N. Bizot, T.Flacke, G. Cacciapaglia]

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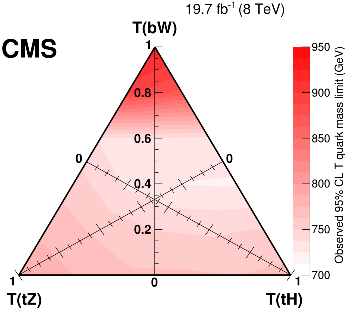
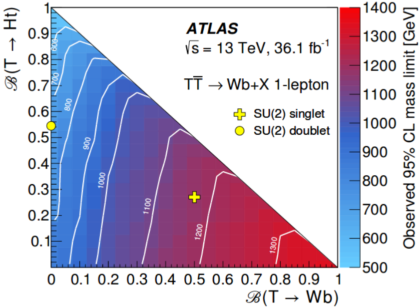
Currents searches focus on VLQs decays into SM particles and assume:

- $Br(T \to Zt, ht, W^+b) = 1$,
- $Br(X_{5/3} \to W^+t) = 1$,
- $Br(B \to Zb, hb, W^-t) = 1$
- $Br(Y_{-4/3} \to W^-b) = 1$

VLQs can be:

- pair produced (QCD) $\Rightarrow$ model-independent
- singly produced (EW) $\Rightarrow$ depends on mixing with SM quarks





Vector-like: left and right-handed chiralities have same quantum number such that mass term is allowed in opposition to SM chiral fermions

Composite Higgs models:

- Higgs emerges as pNGB (like QCD pions) ⇒ Naturally light
- Simplest realisation: four-dimensional gauge theory of fermions (like QCD)

⇒ Non-minimal models [beyond $SO(5)/SO(4)$]

New channels in composite Higgs models (CHMs)

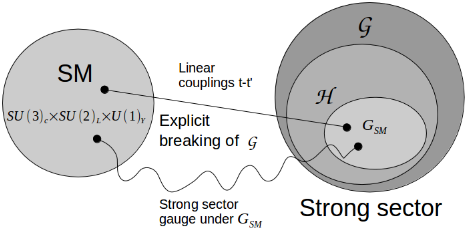
Generic prediction: presence of additional light states (pNGBs) involved in VLQs decays ⇒ 4 promising decay modes

- EW-singlet mode: $T \to \eta t$ [η = EW pNGB like Higgs]
- $U(1)$-mode: $T \to at$ [a = pNGB associated to non-anomalous $U(1)$]
- Coloured mode: $X_{5/3} \to \pi_6 \bar{b}$ [π_6 = Coloured pNGB]
- Charged mode: $X_{5/3} \to \phi^+ t$ [ϕ^+ = EW pNGB like Higgs]

Exotic decays are the norm and commonly appear with significant rates
⇒ Modifies search strategies and affects the VLQs bounds

Well-defined theoretical framework ⇒ couplings predicted not added by hand

- New strong dynamics condensates at scale Λ and spontaneously breaks a global symmetry G into H
  ⇒ Higgs is naturally light as a pNGB leaving in the coset G/H (like QCD pions)
- Potential and mass for the Higgs generated by explicit breaking terms



Partial compositeness

- Linear couplings between top and top partners
  ⇒ induce EWSB and top mass
- Top quark heaviest SM particle
  ⇒ Largest interaction with strong sector
- Induces the new decay modes

Strategy: Choose a model (underlying theory, top partner irreps)
look at benchmark scenarios (fix pre-Yukawa couplings, VL masses)

⇒ Focus on phenomenoloogy

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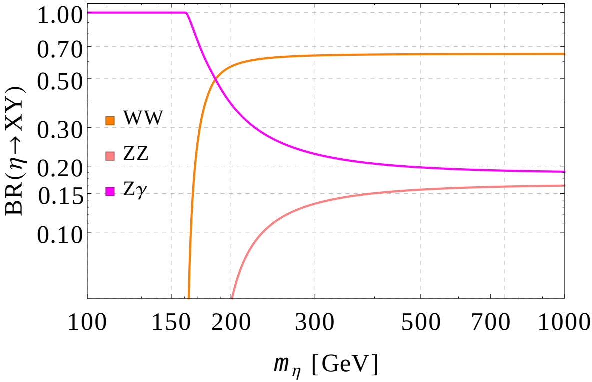
- Lightest VLQ T: pure EW singlet, no mixing with SM quarks

$\Rightarrow$ No single production

- No standard decays as T couples only to ηt (Parity)

$\Rightarrow$ $Br(T \to \eta t) = 1$

EW singlet η decays into SM particles ($m_\eta \gtrsim 100$ GeV as same origin as Higgs boson)



- Anomalous couplings to SM gauge bosons [Cacciapaglia, Deandrea et al, 1502.04718]

$\Rightarrow$ $WW, \gamma Z, ZZ$ decays

$\Rightarrow$ No $\gamma\gamma$ coupling

- No decays into SM fermions

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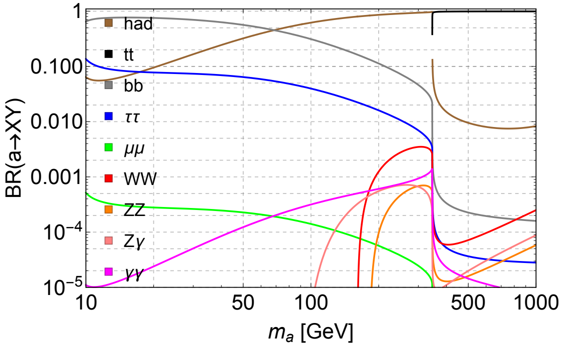
- Lightest VLQ T (mix singlet-doublet) mixes with SM top quark

$\Rightarrow$ Pair and single production relevant

- EW singlet a associated to non-anomalous $U(1)$-symmetry

[Spontaneously broken contrary to $U(1)_V$ in QCD $\to$ a is a pNGB]

$\Rightarrow$ can be very light (10 GeV $\lesssim m_a \lesssim 1$ TeV) as different origin compare to Higgs boson mass



- Anomalous decays into SM gauge bosons

$\Rightarrow$ $gg, WW, ZZ, Z\gamma, \gamma\gamma$

- Decays into all SM fermions

$\Rightarrow$ Couplings proportional to fermion masses (like Higgs)

$\Rightarrow$ Branching strongly depend on m_a

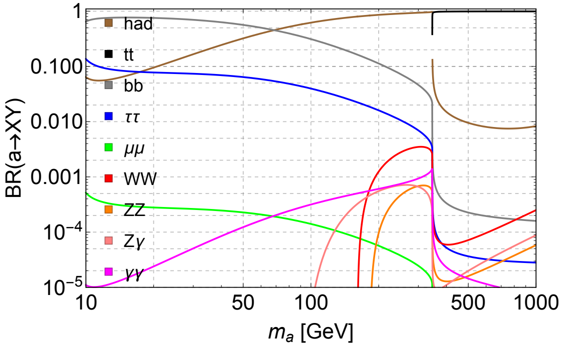
- Lightest VLQ T (mix singlet-doublet) mixes with SM top quark

$\Rightarrow$ Pair and single production relevant

- EW singlet a associated to non-anomalous $U(1)$-symmetry

[Spontaneously broken contrary to $U(1)_V$ in QCD $\to$ a is a pNGB]

$\Rightarrow$ can be very light (10 GeV $\lesssim m_a \lesssim 1$ TeV) as different origin compare to Higgs boson mass



Low mass region:

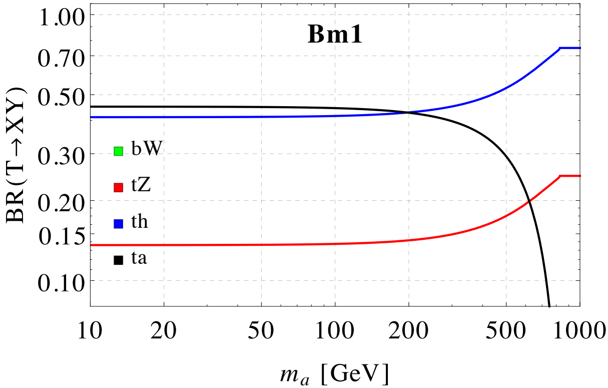
- a decays mainly into $b\bar{b}$, $\tau\tau$ and hadrons

Hight mass region:

- Below $t\bar{t}$ threshold decay mainly into hadrons (also $b\bar{b}$ and $\tau\tau$)

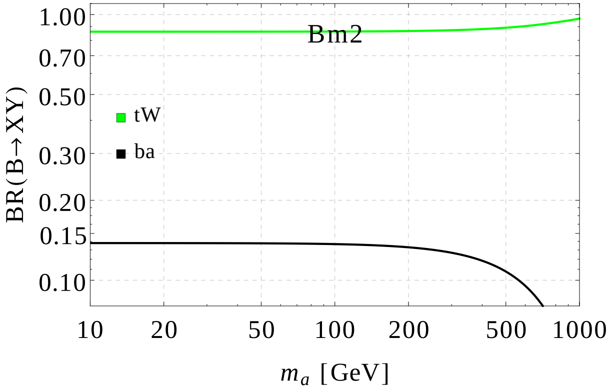
- Above threshold a decays almost exclusively into $t\bar{t}$

- Standard channels + *at*-channel $\Rightarrow$ 4 dimensional parameter space
$\Rightarrow$ Relevant to explore $Br(T \to ht, Wb, Zt) + Br(T \to at) = 1$
(should extend 'triangle' plots)
- Below threshold $T \to at$ dominates in general



$$\text{Bm1}: \quad M_T = 1 \text{ TeV}, \quad \kappa^{T}_{Z,R} = -0.03, \quad \kappa^{T}_{h,R} = 0.06, \quad \kappa^{T}_{a,R} = -0.24, \quad \kappa^{T}_{a,L} = -0.07$$

- Bottom partner can also decay into a
- Larger branching ratio is possible depending on the underlying theory



Bm2 : $M_B = 1.38$ TeV , $\kappa^{B}_{W,L} = 0.02$, $\kappa^{B}_{W,R} = -0.08$, $\kappa^{B}_{a,L} = -0.25$,

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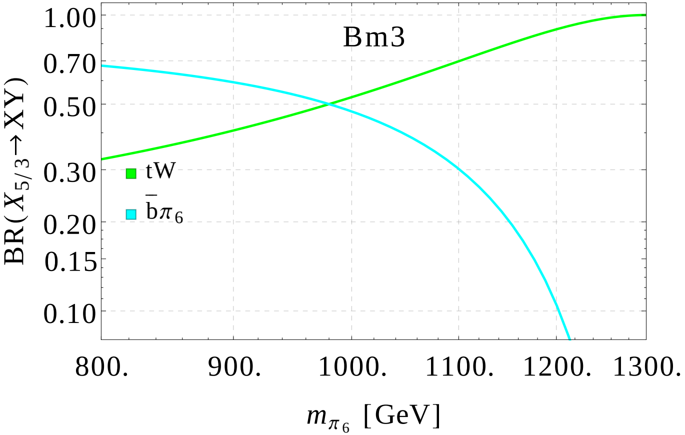
- Lightest VLQ is $X_{5/3}$ is part of EW-doublet $(X_{5/3}\,T) \sim (3, 2, 7/6)$
  $\Rightarrow$ Pair-produced from QCD
- Non-negligible $X_{5/3} \to \pi_6 \bar{b}$ branching ratio w.r.t standard $X_{5/3} \to W^+ t$
  $\Rightarrow$ Two dimensional parameter space

π_6 decays

- pNGB sextet π_6 associated to spontaneously broken global symmetry of the coloured sector (required to form composite VLQs)
  $\Rightarrow$ Direct searches lead to $m_{\pi_6} \gtrsim 800$ GeV [Cacciapaglia, Deandrea, Flacke et al, 1507.02283]
- Decay only into tops $\pi_6 \to tt$ $\pi_6 \sim (6, 1, 4/3)$
  $\Rightarrow$ No decays into SM gauge bosons (hypercharge)
  $\Rightarrow$ No decays into light fermions (partial compositeness vs bilinear coupling)

Relevant to explore $Br(W^+ t) + Br(\pi_6 \bar{b}) = 1$



$$\text{Bm3}: \quad M_{X_{5/3}} = 1.3 \text{ TeV} , \quad \kappa^{X}_{W,L} = 0.03 , \quad \kappa^{X}_{W,R} = -0.11 ,$$
$$\kappa^{X}_{\pi_6,L} = 1.95 , \quad \kappa^{\pi_6}_{tt,R} = -0.56 ,$$

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$X_{5/3} \to \phi^+ t$

- Lightest VLQ is $X_{5/3}$ is part of EW-doublet $(X_{5/3}\, T) \sim (3, 2, 7/6)$

$\Rightarrow$ Pair-produced from QCD

- Non-negligible $X_{5/3} \to \phi^+ t$ branching ratio w.r.t standard $X_{5/3} \to W^+ t$

$\Rightarrow$ Two dimensional parameter space (coloured pNGB can easily be heavier than VLQs)

ϕ^+ decays

- pNGB ϕ^+ is an EW triplet (same origin as the Higgs boson)

$$\Phi_+ = \left(\phi^{++} \quad \phi^+ \quad \phi^0\right)^T \sim (1,3,1)\ , \qquad \Phi_0 = \left(\phi^+ \quad \phi^0 \quad \phi^-\right)^T \sim (1,3,0)\ ,$$

- Anomalous couplings: $\phi^+ \to W^+\gamma$ and $\phi^+ \to W^+ Z$ from $\Phi_0 W^{\mu\nu} \tilde{B}_{\mu\nu}$

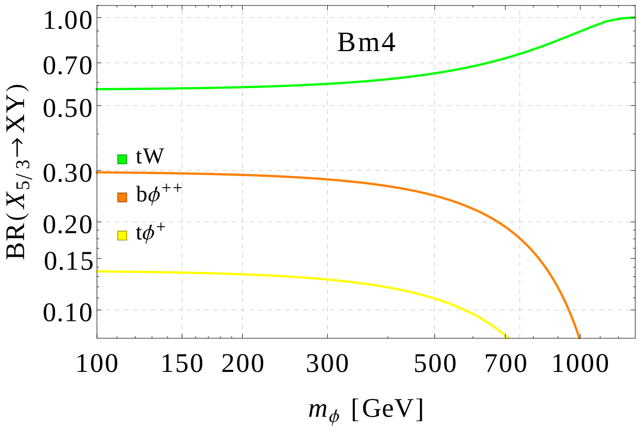
$\Rightarrow$ $W^+\gamma$ channel dominates

- Decays into SM fermions: $\phi^+ \to t\bar{b}$ from $\Phi_+^a (\bar{q}_L \tilde{H})^a b_R$ or $\Phi_0^a (\bar{q}_L H)^a b_R$

(also decays into light quarks and leptons) $\Rightarrow$ Supressed by v/f

- $\Gamma_{\phi^+ W^+ V} \sim m_{\phi^+}^3$ while $\Gamma_{W^+ tb} \sim m_{\phi^+}$ $\Rightarrow$ decays into spin 1 is dominant

Relevant to explore $Br(W^+ t) + Br(\phi^+ t) + Br(\phi^{++} b) = 1$



$$\text{Bm4}: \quad M_{X_{5/3}} = 1.3\ \text{TeV}, \quad \kappa^{X}_{W,L} = 0.03, \quad \kappa^{X}_{W,R} = 0.13,$$
$$\kappa^{X}_{\phi^+,L} = 0.49, \quad \kappa^{X}_{\phi^+,R} = 0.12, \quad \kappa^{X}_{\phi^{++},L} = -0.69, \quad \kappa^{\phi}_{tb,L} = 0.53,$$

- Simplest realisation of composite Higgs model is a 4D gauge theory of fermions that condenses at low energy
$\Rightarrow$ Higgs naturally light as pNGB
$\Rightarrow$ Additional EW pNGB $\eta, \phi^+, \cdots$ (depending on the underlying model)

- EWSB requires partial compositeness for top quark
$\Rightarrow$ Coloured pNGBs $\pi_6, \cdots$ $\Rightarrow$ Additional $U(1)$-singlet a

Final states

- EW-singlet mode: $T \to \eta t$, $\eta \to WW, \gamma Z, ZZ$
  pair-production only , $m_\eta \gtrsim 100$ GeV
- U(1)-mode: $T \to at$, $a \to t\bar{t}$ (hight mass), hadrons, $b\bar{b}, \tau\tau$ (low mass)
  pair+single production, m_a could be very light ~ 10 GeV
- Coloured mode: $X_{5/3} \to \pi_6 \bar{b}$, $\pi_6 \to tt$
- Charged mode: $X_{5/3} \to \phi^+ t$, $\phi^+ \to W^+\gamma, W^+ Z$

Model-dependant scenarios
$\Rightarrow$ Typical behaviour only (benchmarks scenarios from theory side)
$\Rightarrow$ Variations are possible (depending on the model, underlying gauge theory)

Final states

- EW-singlet mode: $T \to \eta t$

Pair production: $pp \to T\overline{T} \to (\eta t)(\eta \bar{t})$, $\eta \to WW, \gamma Z, ZZ$

- U(1)-mode: $T \to at$

Pair production: $pp \to T\overline{T} \to (at)(a\bar{t})$ or $(at)(Z\bar{t}, h\bar{t}, W^-\bar{b})$

Single production: $pp \to T \to at$

- Coloured mode: $X_{5/3} \to \pi_6 \overline{b}$

Pair production: $pp \to X_{5/3}\overline{X}_{5/3} \to (\pi_6 \overline{b})(\pi_6^c b) \to (tt\overline{b})(\bar{t}\bar{t}b)$

$pp \to X_{5/3}\overline{X}_{5/3} \to (W^+ t)(\pi_6^c b) \to (W^+ t)(\bar{t}\bar{t}b)$

- Charged mode: $X_{5/3} \to \phi^+ t$

Pair production: $pp \to X_{5/3}\overline{X}_{5/3} \to (\phi^+ t)(\phi^- \bar{t}) \to (W^+ \gamma t)(W^- \gamma \bar{t})$

$pp \to X_{5/3}\overline{X}_{5/3} \to (W^+ t)(\phi^- \bar{t}) \to (W^+ t)(W^- \gamma \bar{t})$

Back-up

Structure of the underlying theory

Barring extra space-time dimensions:
Simplest, well-understood, explicit realization provided by 4D gauge theory of fermions that confines at the multi-TeV scale Λ

$\Rightarrow$ No fundamental scalar reintroducing hierarchy problem at higher scale

Fundamental fermions

pNGB Higgs + top partners (PC)

$\Rightarrow$ Two species of fundamental fermions (novel feature compare to QCD)

- EW sector (Higgs sector): fermions ψ

$\Rightarrow$ Spontaneous symetry breaking should deliver at least 4 pNGBs associated to Higgs doublet: $H \sim (\psi\psi)$

- Coloured sector: fermions X

$\Rightarrow$ Some trilinear bound states $(\psi\psi X)$ or (ψXX) should have same quantum numbers as SM top quark multiplets

$\Rightarrow$ Spontaneous breaking delivers additional coloured pNGBs $(XX) \sim \pi^c$

Minimal fermionic UV completion

First example provided by:

EW sector $SU(4)/Sp(4) \cong SO(6)/SO(5)$

- $SU(4)/Sp(4) \Rightarrow$ only 15-10 = 5 NGBs: Higgs doublet + singlet η
- 4 Weyl fermions $\psi \Rightarrow SU(4)$ global symmetry
- $Sp(4) \Rightarrow \psi$ belong to a pseudo-real hypercolour representation:
  the fundamental of $Sp(2N)$ [Barnard et al, '13]

Coloured sector $SU(6)/SO(6)$

- $SU(6)/SO(6) \Rightarrow$ 35-15 = 20 coloured NGBs: π_8, π_6 and π_6^c
- 6 Weyl fermions $\chi \Rightarrow SU(6)$ global symmetry
- $SO(6) \Rightarrow \chi$ belong to a real hypercolour representation:
  2-index antisymmetric of $Sp(2N)$

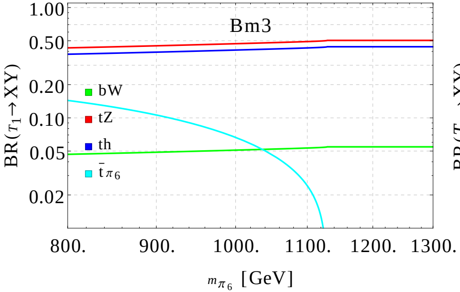
G_{HC}	ψ	χ	Restrictions	$-q_\chi/q_\psi$	Y_χ	Non Conformal	Model Name
	Real	Real	SU(5)/SO(5) × SU(6)/SO(6)				
$SO(N_{\mathrm{HC}})$	$5\times\mathbf{S}_2$	$6\times\mathbf{F}$	$N_{\mathrm{HC}}\geq 55$	$\frac{5(N_{\mathrm{HC}}+2)}{6}$	$1/3$	/	
$SO(N_{\mathrm{HC}})$	$5\times\mathbf{Ad}$	$6\times\mathbf{F}$	$N_{\mathrm{HC}}\geq 15$	$\frac{5(N_{\mathrm{HC}}-2)}{6}$	$1/3$	/	
$SO(N_{\mathrm{HC}})$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$N_{\mathrm{HC}}=7,9$	$\frac{5}{6},\frac{5}{12}$	$1/3$	$N_{\mathrm{HC}}=7,9$	M1, M2
$SO(N_{\mathrm{HC}})$	$5\times\mathbf{Spin}$	$6\times\mathbf{F}$	$N_{\mathrm{HC}}=7,9$	$\frac{5}{6},\frac{5}{3}$	$2/3$	$N_{\mathrm{HC}}=7,9$	M3, M4
	Real	Pseudo-Real	SU(5)/SO(5) × SU(6)/Sp(6)				
$Sp(2N_{\mathrm{HC}})$	$5\times\mathbf{Ad}$	$6\times\mathbf{F}$	$2N_{\mathrm{HC}}\geq 12$	$\frac{5(N_{\mathrm{HC}}+1)}{3}$	$1/3$	/	
$Sp(2N_{\mathrm{HC}})$	$5\times\mathbf{A}_2$	$6\times\mathbf{F}$	$2N_{\mathrm{HC}}\geq 4$	$\frac{5(N_{\mathrm{HC}}-1)}{3}$	$1/3$	$2N_{\mathrm{HC}}=4$	M5
$SO(N_{\mathrm{HC}})$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$N_{\mathrm{HC}}=11,13$	$\frac{5}{24},\frac{5}{48}$	$1/3$	/	
	Real	Complex	SU(5)/SO(5) × SU(3)²/SU(3)				
$SU(N_{\mathrm{HC}})$	$5\times\mathbf{A}_2$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$N_{\mathrm{HC}}=4$	$\frac{5}{3}$	$1/3$	$N_{\mathrm{HC}}=4$	M6
$SO(N_{\mathrm{HC}})$	$5\times\mathbf{F}$	$3\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$N_{\mathrm{HC}}=10,14$	$\frac{5}{12},\frac{5}{48}$	$1/3$	$N_{\mathrm{HC}}=10$	M7
	Pseudo-Real	Real	SU(4)/Sp(4) × SU(6)/SO(6)				
$Sp(2N_{\mathrm{HC}})$	$4\times\mathbf{F}$	$6\times\mathbf{A}_2$	$2N_{\mathrm{HC}}\leq 36$	$\frac{1}{3(N_{\mathrm{HC}}-1)}$	$2/3$	$2N_{\mathrm{HC}}=4$	M8
$SO(N_{\mathrm{HC}})$	$4\times\mathbf{Spin}$	$6\times\mathbf{F}$	$N_{\mathrm{HC}}=11,13$	$\frac{8}{3},\frac{16}{3}$	$2/3$	$N_{\mathrm{HC}}=11$	M9
	Complex	Real	SU(4)²/SU(4) × SU(6)/SO(6)				
$SO(N_{\mathrm{HC}})$	$4\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$6\times\mathbf{F}$	$N_{\mathrm{HC}}=10$	$\frac{8}{3}$	$2/3$	$N_{\mathrm{HC}}=10$	M10
$SU(N_{\mathrm{HC}})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$6\times\mathbf{A}_2$	$N_{\mathrm{HC}}=4$	$\frac{2}{3}$	$2/3$	$N_{\mathrm{HC}}=4$	M11
	Complex	Complex	SU(4)²/SU(4) × SU(3)²/SU(3)				
$SU(N_{\mathrm{HC}})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$N_{\mathrm{HC}}\geq 5$	$\frac{4}{3(N_{\mathrm{HC}}-2)}$	$2/3$	$N_{\mathrm{HC}}=5$	M12
$SU(N_{\mathrm{HC}})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{S}_2,\overline{\mathbf{S}}_2)$	$N_{\mathrm{HC}}\geq 5$	$\frac{4}{3(N_{\mathrm{HC}}+2)}$	$2/3$	/	
$SU(N_{\mathrm{HC}})$	$4\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$N_{\mathrm{HC}}=5$	4	$2/3$	/	

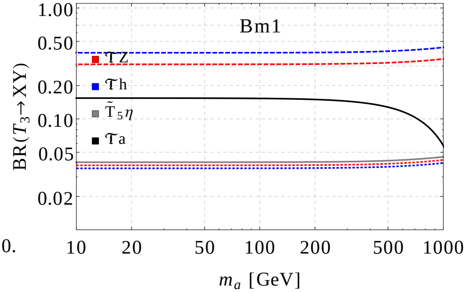
Several other possibilities exist:

- Different EW and coloured cosets
- Fundamental fermions in different irreps
- Change anomalous couplings: Branching ratios of pNGBs
- Change VLQs couplings to pNGBs (values of decay constants, $\cdots$)

VLQs: 5-plet $\rightarrow \begin{pmatrix} X_{5/3} \\ X_{2/3} \end{pmatrix}, \quad \begin{pmatrix} T \\ B \end{pmatrix}, \quad \tilde{T}_5$ singlet $\rightarrow \tilde{T}_1$

$$\bar{\psi}_{tR} \begin{pmatrix} 0 & -\frac{y_{5R}}{\sqrt{2}} e^{i\xi_5 \frac{a}{f_a}} f s_\theta & -\frac{y_{5R}}{\sqrt{2}} e^{i\xi_5 \frac{a}{f_a}} f s_\theta & y_{1R} e^{i\xi_1 \frac{a}{f_a}} f c_\theta & i y_{5R} c_\theta \eta \\ y_{5L} e^{i\xi_5 \frac{a}{f_a}} f c^2_{\theta/2} & M_5 & 0 & 0 & 0 \\ -y_{5L} e^{i\xi_5 \frac{a}{f_a}} f s^2_{\theta/2} & 0 & M_5 & 0 & 0 \\ -\frac{y_{1L}}{\sqrt{2}} e^{i\xi_1 \frac{a}{f_a}} f s_\theta & 0 & 0 & M_1 & 0 \\ -i \frac{y_{5L}}{\sqrt{2}} s_\theta \eta & 0 & 0 & 0 & M_5 \end{pmatrix} \psi_{tL}$$





$\Rightarrow$ Richer phenomenology as compare to effective model with only one VLQ

Additional pNGBs

In addition to the Higgs doublet, additional EW pNGBs are present

EW sector

Smallest cosets constructed from pseudoreal, real or complex representations:

- $SU(4)/Sp(4)$: $5_{Sp(4)} \equiv \mathbf{A}_2 = 2_{\pm 1/2} + 1_0$ (H, η)
- $SU(5)/SO(5)$: $14_{SO(5)} \equiv \mathbf{S}_2 = 3_{\pm 1} + 3_0 + 2_{\pm 1/2} + 1_0$ $(\Phi_\pm, \Phi_0, H, \eta)$
- $SU(4) \times SU(4)/SU(4)$: $15_{SU(4)} \equiv \mathbf{Ad} = 3_0 + 2_{\pm 1/2} + 2_{\pm 1/2} + 1_{\pm 1} + 1_0 + 1_0$
  [Ma, Cacciapaglia, 1508.0714] $(\Phi_0, H_1, H_2, N_\pm, N_0, \eta)$

$\Rightarrow$ Always SM-like singlet η $\Rightarrow$ Sometimes triplets or second Higgs doublet

Coloured sector

- $SU(6)/SO(6) \supset SU(3)_c$: $20'_{SO(6)} \equiv \mathbf{A}_2 = 8_0 + 6_{4/3} + \overline{6}_{-4/3}$ (π_8, π_6, π_6^c)
- $SU(6)/Sp(6) \supset SU(3)_c$: $14_{Sp(6)} \equiv \mathbf{S}_2 = 8_0 + 3_{-4/3} + \overline{3}_{4/3}$ (π_8, π_3, π_3^c)
- $SU(3) \times SU(3)/SU(3)_c$: $8_{SU(3)} \equiv \mathbf{Ad} = 8_0$ (π_8)

$\Rightarrow$ Always a coloured octet π_8 $\Rightarrow$ Sometimes coloured triplets or sextets

[Cacciapaglia et al, 1507.02283, 1610.06591]

Anomalous couplings

pNGBs may couple to gauge bosons through anomalies ($\pi^0 \to \gamma\gamma$ in QCD)

$$\mathcal{L}^{WZW} = -\frac{g_{\mathcal{W}}^2}{64\pi^2}\frac{d_{HC}}{F_G}\epsilon_{\mu\nu\rho\sigma}\mathcal{W}^{\mu\nu}\mathcal{W}^{\rho\sigma}\sum_{\hat{A}} d^{WW\hat{A}} G^{\hat{A}} + \cdots$$

$$d^{WW\hat{A}} = 2\,Tr(\{T^W, T^W\}T^{\hat{A}})$$

$\Rightarrow$ Non-zero couplings depend on the coset (global symmetries)
$\Rightarrow$ Stength depends on the underlying theory (fundamental fermions irreps)

EW pNGBs

- No anomalous couplings for the Higgs boson
- $SU(4)/Sp(4)$ ηZZ, $\eta\gamma Z$, ηWW
- $SU(5)/SO(5)$ $\eta\gamma\gamma$ ηZZ, $\eta\gamma Z$, ηWW, triplet anomalous couplings, $\cdots$

Coloured pNGBs

- π_8 decays in gg, γg or Zg via anomaly (and top triangle loop)

In general PC implies decays of pNGBs into tops ($\eta \to t\bar{t}$, $\pi_6 \to tt$, $\cdots$)

Non-anomalous U(1) symmetry

- EW ψ fermions: anomalous $U(1)_\psi$
- Coloured X fermions: anomalous $U(1)_X$

$\Rightarrow$ Always a non-anomalous combination w.r.t hypercolour

$$q_\psi N_\psi T(\psi) + q_X N_X T(X) = 0$$

$\Rightarrow$ One additional light pNGB a

$\Rightarrow$ Other pseudoscalar η' receive mass from anomaly (instanton effects), could be light as no way to estimate anomaly coefficient

Anomalous couplings

- η_ψ to $SU(2)_L \times U(1)_Y$ gauge bosons ($\eta_\psi WW, BB$) [Cai et al, 1512.04508]
- η_X to $SU(3)_c \times U(1)_Y$ gauge bosons ($\eta_X gg, BB$)

$\eta_\psi - \eta_X$ mixing:

$$\begin{cases} a = \cos\phi\ \eta_\psi + \sin\phi\ \eta_X \\ \eta' = -\sin\phi\ \eta_\psi + \cos\phi\ \eta_X \end{cases} \qquad \tan\phi = \frac{f_X q_X}{f_\psi q_\psi}$$

$\Rightarrow$ a produced by gluon fusion (contrary to EW pNGBs)

$\Rightarrow$ a decays to dibosons ($gg, WW, ZZ, Z\gamma, \gamma\gamma$) and $t\bar{t}$ thanks to PC [Belyaev et al, 1610.06591]