Composite models - 2
Experimental signatures

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From the theory to the experimental side

Theoretical motivations from SM

- Hierarchy problem
  (cf Giacomo talk)
- Large top quark mass

↓

Model of New physics

- Composite pNGB Higgs
- Partial compositeness (PC)

↓

Experimental predictions

- Deviations SM couplings
  (Non-linear EWSB)
- Light top parners
- Other light pNGBs

Basics ideas of composite Higgs models

- 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

Spontaneous symmetry breaking via confinement ia a phenomenon already observed in nature:
QCD: $G/H = SU(3)_L \times SU(3)_R/SU(3)_V \rightarrow$ 8 pNGBs $(\pi^\pm, \pi^0, K^\pm, K^0\overline{K}^0, \eta)$

- Potential and mass for Higgs generated by explicit breaking terms

⇒ Links between the elementary and composite sectors
⇒ Current masses (like in QCD), $\cdots$

Gauging of SM symmetry

- SM gauge symmetry embedded inside unbroken group H

⇒ pNGBs charged under G_{SM} (4 associated to Higgs doublet)
⇒ Can not destabilise Higgs potential and induce EWSB $(\Delta M_H^2 > 0)$

Basics ideas of composite Higgs models

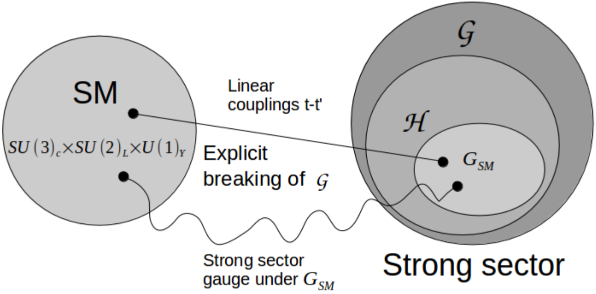
Partial compositeness

- Another explicit breaking is required

⇒ Linear couplings between top and top partners induce EWSB and top mass
(more generally linear couplings for all SM fermions)

- Top quark is the heaviest SM particle

⇒ Largest interaction with strong sector



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: 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

Underlyig theory should provide viable Higgs sector and appropriate coloured fermionic bound states

Model building

Models considered are vector-like gauge theory: all fermions ψ, χ can be made massive, while preserving the gauge hypercolour symmetry G_{HC}

Three cases: [Peskin, '80]

- $G = SU(N_f)_L \times SU(N_f)_R$ and $H_m = SU(N_f)_V$ (complex rep. of G_c like in QCD)
- $G = SU(2N_f)$ and $H_m = SO(2N_f)$ (real rep.)
  $H_m = Sp(2N_f)$ (pseudo-real rep.)

N_f = Number of Weyl fermions in a given representation of G_{HC}
$\Rightarrow$ Symmetry breaking pattern determined only by irreps of underlying fermions

First viable model

Before fermionic UV completions, lot of attention has been devoted to:

$$G/H = SO(5)/SO(4) \cong SU(2)_L \times SU(2)_R$$

- Very challenging to obtain from a 4D fermionic theory
- EW pNGB spectrum contains only Higgs doublet
- No coloured sector

$\Rightarrow$ Collider searches have focused on top partners because of the lack of EW and coloured additional scalars
$\Rightarrow$ To explore in more generality the experimental signatures of CHMs one needs to go beyond $SO(5)/SO(4)$ coset

Minimal fermionic UV completion

First example provided by: $G/H = SU(4)/Sp(4) \cong SO(6)/SO(5)$

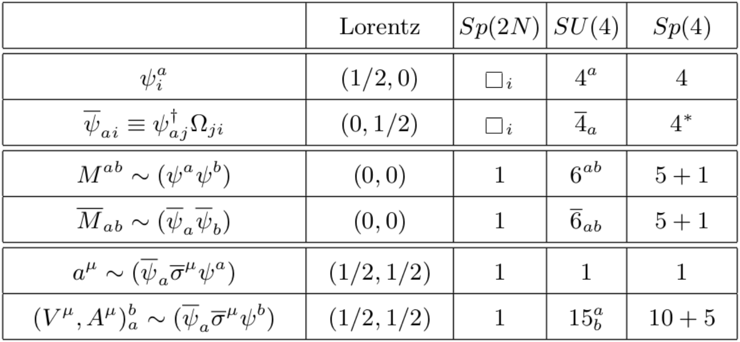
EW sector $SU(4)/Sp(4) \cong SO(6)/SO(5)$

- $SU(4)/Sp(4) \Rightarrow$ 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:
- 6 Weyl fermions $\chi \Rightarrow SU(6)$ global symmetry
- $SO(6) \Rightarrow \chi$ belong to a real hypercolour representation: 2-index antisymmetric of $Sp(2N)$

Lightest EW mesons in the minimal fermionic UV completion



			Colour	Flavour	
		Lorentz	$Sp(2N)$	$SU(4)$	$Sp(4)$
Hypercolour fermions	ψ_i^a	$(1/2, 0)$	$\square_i$	4^a	4
	$\overline{\psi}_{ai} \equiv \psi_{aj}^{\dagger}\Omega_{ji}$	$(0, 1/2)$	$\square_i$	$\overline{4}_a$	4^*
Spin-zero bilinears	$M^{ab} \sim (\psi^a \psi^b)$	$(0, 0)$	1	6^{ab}	$5 + 1$
	$\overline{M}_{ab} \sim (\overline{\psi}_a \overline{\psi}_b)$	$(0, 0)$	1	$\overline{6}_{ab}$	$5 + 1$
Spin-one bilinears	$a^\mu \sim (\overline{\psi}_a \overline{\sigma}^\mu \psi^a)$	$(1/2, 1/2)$	1	1	1
	$(V^\mu, A^\mu)_a^b \sim (\overline{\psi}_a \overline{\sigma}^\mu \psi^b)$	$(1/2, 1/2)$	1	15_b^a	$10 + 5$

Hypercolour-invariant fermionic bilinears have the quantum numbers of the meson resonances

Lightest composite meson resonances

Scalars: $\sigma + S^{\hat{A}} \sim 1 + 5$

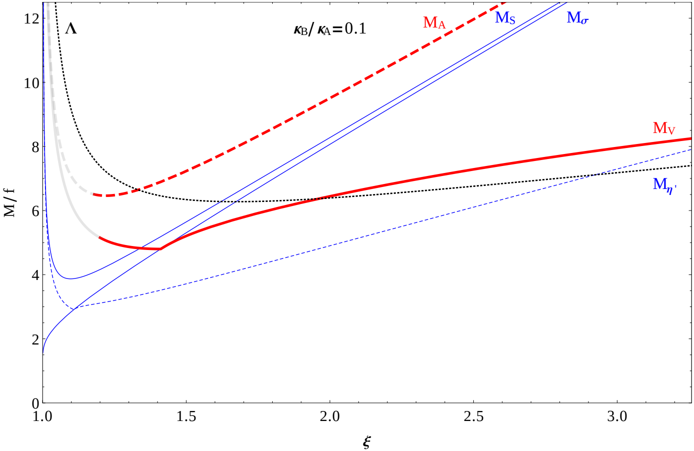
Pseudo-scalars: $\eta' + G^{\hat{A}} \sim 1 + 5$

Vectors: $V_\mu^A \sim 10$

Axial-vector: $a_\mu + A_\mu^{\hat{A}} \sim 1 + 5$

Spin one resonances

[Bizot et al, 1610.09293]



Estimation of mass spectrum using NJL techniques

Spin-one resonances usually included in CHMs analyses

$\Rightarrow$ Masses of the order of the condensation scale Λ or above

$\Rightarrow$ Justify to focus experimentally on pNGBs

Effective approach

Full gauge theory (hypergluons, hyperfermions as d.o.f) hard to study below condensation scale Λ because of its non-perturbative nature

⇒ Most of the works have focused only on the chiral Lagrangian approach

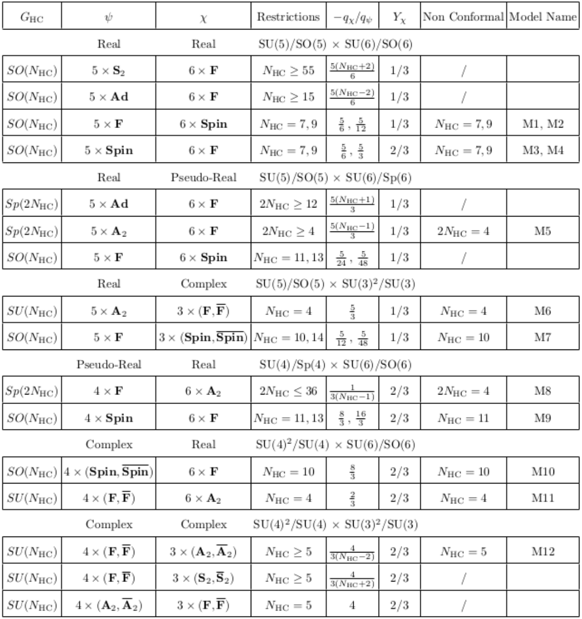
$$\mathcal{L}_{\chi PT} = \frac{f^2}{8}\mathrm{Tr}[D_\mu \Sigma^\dagger D^\mu \Sigma] \qquad \Sigma = \exp(2\sqrt{2} i G^{\hat{A}} T^{\hat{A}}/f)\Sigma_0$$

- Not sure that an UV completion exists ie $SO(5)/SO(4)$
- Some informations may be missing: existence of two fundamental sectors with additional pNGBs, $\cdots$

⇒ Useful to have a definite UV completion before using an effective theory to make computations

Also possible to compute non-perturbative quantities like masses of composite resonances starting from 4-fermions interactions within the NJL model [Bizot et al, 1610.09293]

List of "minimal" UV completions



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

[Belyaev et al, 1610.06591]

Motivation of the talk

Lot of motivated fermionic UV completions
⇒ Goal is to isolate the general predictions common to all CHMs

Framework

Confinig hypercolour gauge theory with only fermionic matter fields:

- pNGB Higgs boson (bound state of 2 hyperfermions)
- top partners as bound states of 3 hyperfermions

⇒ All models have additional pNGBs that should be accessible at LHC

⇒ First evidence may come from discovery of additional pNGBs rather than direct observation of top partners

- Extended Higgs sector: singlet, second Higgs doublet, $\cdots$
- Additional Pseudoscalars singlets η_0 and η' linked to global $U(1)$ symmetries
- Coloured mesons from presence of coloured underlying fermions (always octet but also triplets or sextets)
- Top partners: Usual decays $t' \to Zt, ht, Wb$ and exotic ones like $t' \to \eta_0 t$

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Additional pNGBs

In addition to the Higgs doublet, additional EW pNGBs (depending on the coset) are present

Lowest dimensional cosets

Smallest cosets constructed from pseudoreal, real or complex representations:

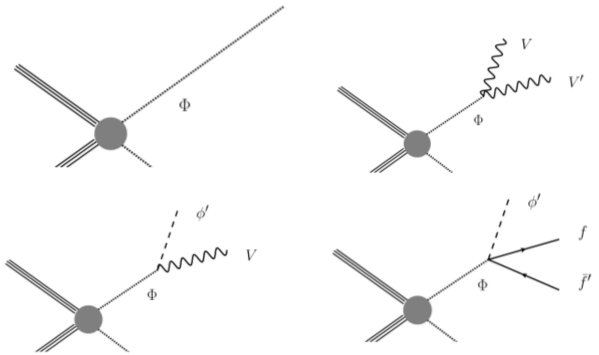
- $\underline{SU(4)/Sp(4)}$: $5_{Sp(4)} \equiv \mathbf{A}_2 = 2_{\pm 1/2} + 1_0$ (H, η)
- $\underline{SU(5)/SO(5)}$: $14_{SO(5)} \equiv \mathbf{S}_2 = 3_{\pm 1} + 3_0 + 2_{\pm 1/2} + 1_0$ $(\phi_\pm, \phi_0, H, \eta)$
- $\underline{SU(4) \times SU(4)/SU(4)}$: $15_{SU(4)} \equiv \mathbf{Ad} = 3_0 + 2_{\pm 1/2} + 2_{\pm 1/2} + 1_{\pm 1} + 1_0 + 1_0$
[Ma, Cacciapaglia, 1508.0714] $(\phi_0, H_1, H_2, N_\pm, N_0, \eta)$

$\Rightarrow$ Always a SM-like (also G_c-invariant) singlet η
$\Rightarrow$ Composite 2HDM
$\Rightarrow$ Scalar triplets
$\Rightarrow$ $\cdots$

Another intersting coset:

- $\underline{SU(6)/Sp(6)}$: 14 PNGBs, 2HDM

Collider signatures



[Ferretti, 1604.06467]

ϕ, ϕ' generic EW pNGBs

After pair-production through off-shell vector boson or VBF EW pNGBs can:

- Be collider stable
- Decay to vector bosons V, V' via anomaly
- Decay to lighter pNGB ϕ' plus vector boson V
- Decay to pair of SM fermions f, f' (plus lighter pNGB ϕ' if P_π-Parity unbroken) $\Rightarrow t\bar{t}$ mainly

Non-linear realisation of the EW symmetry

A lot of information can be extracted from the effective theory

χpT for real and pseudoreal cosets

- LO chiral Lagrangian:

$$\mathcal{L} = \frac{f^2}{8} Tr[(D_\mu \Sigma)(D^\mu \Sigma)^\dagger] \,, \qquad \Sigma = \exp(i2\sqrt{2} G^{\hat{A}} T^{\hat{A}}/f)\Sigma_0$$

- Covariant derivative:

$$D_\mu \Sigma = \partial_\mu \Sigma - i j_\mu \Sigma - i \Sigma j_\mu^T \,, \qquad j_\mu = v_\mu^A T^A + a_\mu^{\hat{A}} T^{\hat{A}}$$

- Goldstone decay constant F_G:

$$\langle 0 | \mathcal{J}_\mu^{\hat{A}}(0) | G^{\hat{B}}(p) \rangle = i F_G p_\mu \delta^{\hat{A}\hat{B}}$$

Expanding Lagrangian aroun vacuum we get

$$\mathcal{L} = \frac{1}{2} \partial_\mu G^{\hat{A}} \partial^\mu G^{\hat{A}} - F_G \partial_\mu G^{\hat{A}} a^{\mu \hat{A}} + \cdots$$

$\Rightarrow$ Kinetic term correctly normalised $\qquad \Rightarrow f \equiv \sqrt{2} F_G$

$\Sigma_0 \equiv$ EW vaccum alignment $\qquad \Sigma_0^2 = \varepsilon \mathbb{1}$ where $\varepsilon = \pm 1$ real (symmetric)
pseudoreal (antisymmetric)

$$Tr[T^A T^B] = 1/2 \delta^{AB}, \qquad T^A \Sigma_0 + \Sigma_0 (T^A)^T = 0$$
$$Tr[T^{\hat{A}} T^{\hat{B}}] = 1/2 \delta^{\hat{A}\hat{B}} \qquad T^{\hat{A}} \Sigma_0 - \Sigma_0 (T^{\hat{A}})^T = 0$$

Vacuum alignment

Consider $SU(4)/Sp(4)$ coset as an example → only one additional pNGB η

Vacuum alignment

- Two physically different vacua: [Cacciapaglia, Sannino, 1402.0233]

$$\Sigma_B = \begin{pmatrix} i\sigma_2 & 0 \\ 0 & -i\sigma_2 \end{pmatrix} \qquad \Sigma_H = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$\Rightarrow$ Σ_B preserves the full EW symmetry, Σ_H breaks it fully to $U(1)_{EM}$

- Vacuum of the theory is a superposition of $\Sigma_{B,H}$

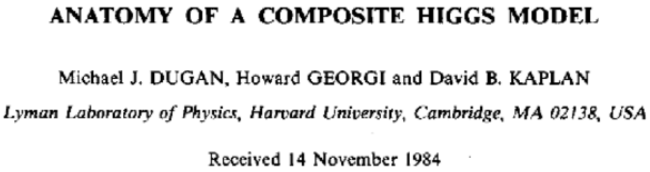
$$\Sigma_0 = \cos\theta\ \Sigma_B + \sin\theta\ \Sigma_H$$

• $\theta = \pi/2 \rightarrow$ Technicolour limit • $\theta \ll 1 \rightarrow$ Composite Higgs limit

- Σ_0 gives alignment of $Sp(4)$ vacuum w.r.t EW embedding

$\Rightarrow \sin\theta \equiv s_\theta = v/f$

Vacuum alignment



ANATOMY OF A COMPOSITE HIGGS MODEL

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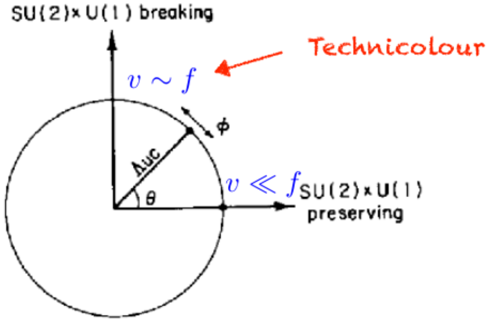
Received 14 November 1984



$$\sin\theta \sim \frac{v}{f}$$

Higgs and η couplings to SM gauge bosons

Using explicit form of broken an unbroken generators and identifying h and η we get their couplings to gauge bosons

Higgs couplings deviations

$$\frac{g_{hVV}}{g_{hVV}^{SM}} = c_\theta = \sqrt{1-\frac{v^2}{f^2}}, \qquad \frac{g_{hhVV}}{g_{hhVV}^{SM}} = c_{2\theta} = 1-2\frac{v^2}{f^2}, \qquad V = \{W, Z\}$$

⇒ Same deviations in all CHMs

⇒ f constrains by Higgs searches (also by EWPT) to be small (cf Giacomo talk)

f crucial parameter in CHMs as it sets the scale of the composite sector and then of the composite resonances masses

η couplings

Kinetic term invariant under P_π-parity $\eta \to -\eta$ that forbids ηVV couplings

$$\frac{g_{\eta\eta VV}}{g_{hhVV}^{SM}} = -s_\theta^2 = -\frac{v^2}{f^2}$$

⇒ P_π-parity not symmetry of underlying theory ie anomalous ηVV couplings: η can not be DM candidate

⇒ In general some trilinear $\pi\pi' V$ couplings are present

Anomalous couplings

Some 3-points functions involving an odd number (*VVA* and *AAA*) of Noether current receive anomalous contributions:

- SM gauge bosons associated to some vector currents V
- pNGBs couple to axial currents A with strength F_G

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

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

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

- No anomalous couplings for the Higgs boson
- η decays through anomalous couplings ηZZ, $\eta\gamma Z$, ηWW

- $SU(5)/SO(5)$ $\eta\gamma\gamma$ ηZZ, $\eta\gamma Z$, ηWW
- $SU(4)\times SU(4)/SU(4)$: same as $SU(4)/Sp(4)$ for η but no anomalies for triplets ϕ and singlets N

⇒ Anomalous couplings completely dependent of the coset

Explicit breaking sources (1)

To generate Higgs potential and break EW symmetry one introduces explicit breaking terms in the chiral theory [Cacciapaglia, Sannino, 1402.0233]

- Gauge contributions:

$$V_{SU(2)} = C_g g^2 f^4 \mathrm{Tr}[T_L^A \Sigma (T_L^A)^T \Sigma^\dagger] = C_g g^2 (-\tfrac{3}{2} f^4 c_\theta^2 + \cdots)$$

$\Rightarrow$ minimum at $\theta = 0$ ie does not break EW symmetry
$\Rightarrow$ Similar contribution from $U(1)_Y$

- Top contributions: Assume 4-fermion operator: $\frac{y_t}{\Lambda_t^2}(Qt^c)^\dagger_\alpha \psi^T P^\alpha \psi$

$P^\alpha \equiv$ projector selecting $SU(2)_L$-doublet component of $\psi^T\psi$

$$V_{top} = -C_t y_t' f^4 \mathrm{Tr}[P^\alpha \Sigma]^2 = -C_t y_t' (f^4 s_\theta^2 + \cdots)$$

$\Rightarrow$ minimum at $\theta = \pi/2$ ie breaks EW symmetry as expected

$$y_t' f (Qt^c)^\dagger_\alpha \mathrm{Tr}[P^\alpha \Sigma] = -y_t'(f s_\theta + c_\theta h \cdots) t_R t_L^c \longrightarrow \frac{y_{h\bar{t}t}}{y_{h\bar{t}t}^{SM}} = c_\theta = \sqrt{1 - \frac{v^2}{f^2}}$$

$\Rightarrow$ Deviation strongly depends on the choosen top parter representation
$\Rightarrow$ $\eta\bar{t}t$ coupling generated in general at NLO (PC breaks P_π-Parity)

Explicit breaking sources (2)

- Current mass contribution:

Explicit mass term for ψ should preserve SM symmetry: $M = \mu \Sigma_B$

$$V_m = C_m f^4 \mathrm{Tr}[\Sigma_B \Sigma] = C_m(-4f^4 c_\theta + \dots)$$

$\Rightarrow$ Does not break EW symmetry like gauge contributions

Adding all contributions

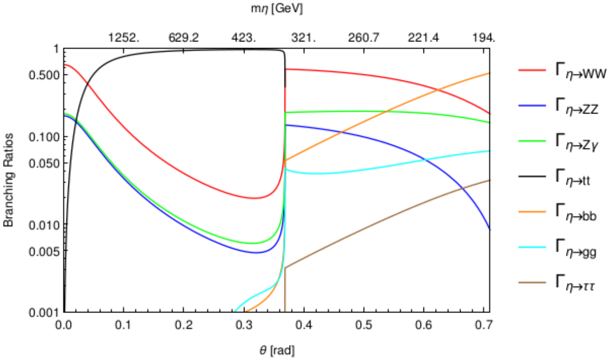
$$V(\theta) = X_t c_\theta^2 - 4X_m c_\theta + cte$$

$V(\theta)$ minimized for:
- $\theta = 0$ (No EWSB)
- $c_\theta = 2X_m/X_t$ if $X_t > 2|X_m|$ (broken EW symmetry)

$\Rightarrow$ At LO, current mass necessary for the CHM limit ($\theta \ll 1$)
$\Rightarrow$ pNGBs masses not independent: $m_\eta^2 = m_h^2/s_\theta^2$

η phenomenology

Higgs couplings measurements and EWPT leads to $\theta \lesssim 0.2 - 0.3$
$\Rightarrow$ Small changes in Higgs phenomenology
$\Rightarrow$ Phenomenology of additional pNGB η interesting



[Arbey et al, 1502.04718]

- θ-bound restricts to the heavy mass region $m_\eta \gtrsim 500$ GeV

$\Rightarrow$ $t\bar{t}$ decay dominates in general otherwise anomalous ηWW, $\eta Z\gamma$, $\eta\gamma\gamma$ dominate

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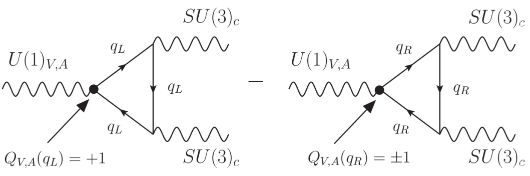
Non-anomalous U(1) symmetry

QCD example: One complex sector

- N_f q_L and N_f q_R → $SU(N_f)_L \times SU(N_f)_R \times U(1)_L \times U(1)_R$ global symmetry



- $U(1)_{L,R}$ anomalous w.r.t $SU(3)_c$ but one combination is not

$\Rightarrow$ $U(1)_V$ is a good symmetry ie non-anomalous

$$V^\mu = R^\mu + L^\mu$$

$\Rightarrow$ Axial $U(1)_A$ anomaly

$$A^\mu = R^\mu - L^\mu$$

U(1) anomalies in CHMs: Two sectors

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

$\Rightarrow$ Always a non-anomalous combination w.r.t hypercolour (spontaneously broken contrary to QCD)

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

$\Rightarrow$ One additional light pNGB η_0

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

$SU(4) \times SU(6)/Sp(4) \times SO(6)$: $N_\psi = 4,\ T(\psi) = 1/2,\ N_X = 6,\ T(X) = (N_{HC} - 1)$

Anomalous couplings

η_0 is a pNGB $\Rightarrow$ Anomalous couplings to SM gauge bosons (like η)

$\eta_\psi - \eta_X$ mixing

Anomalous couplings: [Cai et al, 1512.04508]

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

Conserved $U(1)$ current $j_\mu \propto (f_\psi q_\psi \eta_\psi + f_X q_X \eta_X) \Rightarrow \eta_\psi - \eta_X$ mixing

$$\begin{cases} \eta_0 = \cos\phi\ \eta_\psi + \sin\phi\ \eta_X \\ \eta' = -\sin\phi\ \eta_\psi + \cos\phi\ \eta_X \end{cases} \qquad \tan\phi = \frac{f_X q_X}{f_\psi q_\psi}$$

$\Rightarrow$ η_0 produced by gluon fusion

$\Rightarrow$ η_0 decays to dibosons ($gg, WW, ZZ, Z\gamma, \gamma\gamma$)

$\Rightarrow$ $\eta_0 t\bar{t}$ coupling always arises from PC [Belyaev et al, 1610.06591]

- η' heavier than η_0 as not pNGB but could also be interesting
- Other EW pNGB singlet η has no anomalous couplings to gg (not part of coloured sector): more difficult to produce it

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Coloured sectors

PC forces us to introduce coloured fundamental fermions that form baryons
⇒ schematically two types: $(\psi\psi X)$ or $(\psi X X)$

$X = (\chi, \tilde{\chi}) = 3_{2/3} + \overline{3}_{-2/3}$ $3 \times 3 = \overline{3} + 6$ $3 \times \overline{3} = 1 + 8$

Lowest dimensional cosets

- $\underline{SU(6)/SO(6) \supset SU(3)_c}$: $20'_{SO(6)} \equiv \mathbf{A}_2 = 8_0 + 6_{4/3} + \overline{6}_{-4/3}$ $(O_c, S_c, \overline{S}_c)$
- $\underline{SU(6)/Sp(6) \supset SU(3)_c}$: $14_{Sp(6)} \equiv \mathbf{S}_2 = 8_0 + 3_{-4/3} + \overline{3}_{4/3}$ $(O_c, T_c, \overline{T}_c)$
- $\underline{SU(3) \times SU(3)/SU(3)_c}$: $8_{SU(3)} \equiv \mathbf{Ad} = 8_0$ (O_c)

⇒ Always a coloured octet O_c ⇒ Sometimes coloured triplets or sextets

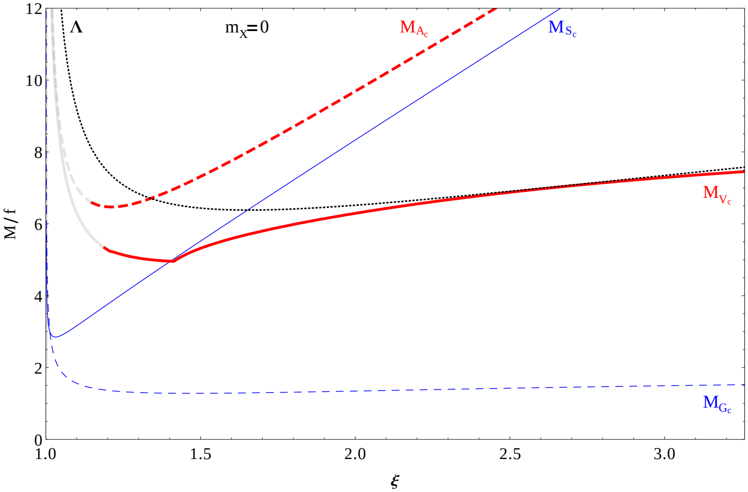
Masses

$$\Delta M^2_{O_c} = -\frac{3}{4\pi} \times \frac{1}{F^2_{G_c}} \int_0^\infty dQ^2\, Q^2\, \Pi^X_{V\text{-}A}(-Q^2) \times \frac{3}{4\pi} g_s^2$$

$$\Delta M^2_{S_c} = -\frac{3}{4\pi} \times \frac{1}{F^2_{G_c}} \int_0^\infty dQ^2\, Q^2\, \Pi^X_{V\text{-}A}(-Q^2) \times \frac{1}{4\pi} \left(\frac{10}{3} g_s^2 + \frac{16}{9} g'^2\right)$$

⇒ Gauge contribution (gluon loops) to masses can be computed using NJL
⇒ Masses in multi-TeV range ie enough to comply with direct searches

Mass of coloured mesons



[Bizot et al, 1610.09293]

Octets

Focus on coloured octet as they appear in all CHMs
[Cacciapaglia et al, 1507.02283, 1610.06591]

Production

- Mainly pair production via QCD interaction
- Singly produced by gluon fusion

Decays channels

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

$$\Gamma_{gg} : \Gamma_{g\gamma} : \Gamma_{gZ} = \frac{5}{6}\alpha_S^2 : 4Y_X^2\alpha_S\alpha : 4Y_X^2\alpha_s\alpha\tan^2\theta_w$$

$\Rightarrow$ gZ always suppressed by Weinberg angle

- Decay in $t\bar{t}$: strongly depends on the details of the model as coupling depends on top partner representation

- Pair production: $4t$, $4g$: two di-jets, $(g\gamma)(gg)$:di-jet with same invariant mass as photon-jet resonance, $(g\gamma)(t\bar{t})$, $(gZ_{ll})(gg)$, $(gZ_{ll})(t\bar{t})$, $\cdots$
- Single production: $t\bar{t}$, gg, $g\gamma$, gZ

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3. Coloured pNGBs
4. Top partners

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Generalities about Vector-like quarks

Addition of new fermions provides simple extensions of the SM:

- Chiral fermions are excluded: Not possible to comply with Higgs searches

(in particular hgg for coloured fermions or $h\gamma\gamma$ for charged fermions)

- Vector-like: Two chiralities have the same SM quantum numbers

$\Rightarrow$ Dirac mass M independent of Higgs vev

$\Rightarrow$ Contributions to loop-induced Higgs processes decouple with M

$\Rightarrow$ VLQs appear in CHMs to realise PC: linear coupling between top and t'

(top partners receive VL mass from strong dynamics like proton and neutron in QCD)

Consider one VLQ → seven multiplets may mix with SM quarks:

- Singlets: $T \sim (3, 1, 2/3)$ $B \sim (3, 1, -1/3)$
- Doublets: $X_T \sim (3, 2, 7/6)$ $Q \sim (3, 2, 1/6)$ $Y_B \sim (3, 2, -5/6)$
- Triplets: $X_Q \sim (3, 3, 2/3)$ $Y_Q \sim (3, 3, -1/3)$

SM-like charges: $Q(t') = 2/3,\ Q(b') - 1/3$

Exotic charges: $Q(X) = 5/3,\ Q(Y) = -4/3$

Mixing between VLQs and SM quarks

Lagrangians

- Singlets and triplets:

$$-\mathcal{L}_\psi = \lambda_\psi \overline{q_L}\tilde{H}(H)\psi_R + M_\psi \overline{\psi_L}\psi_R + h.c.\ , \qquad \text{for } \psi = T, X_Q(B, Y_Q)$$

- Doublets:

$$-\mathcal{L}_\psi = \lambda^t_\psi \overline{\psi_L}\tilde{H}(H)t_R + \lambda^b_\psi \overline{\psi_L}H(\tilde{H})b_R + M_\psi \overline{\psi_L}\psi_R + h.c.\ , \qquad \text{for } \psi = Q(X_T, Y_B)$$

Mixing and decays

$$\mathcal{M}_t = \begin{pmatrix} \lambda_t \frac{v}{\sqrt{2}} & \kappa^t_\psi \lambda_\psi \frac{v}{\sqrt{2}} \\ 0 & M_\psi \end{pmatrix}$$

for $\psi = T, X_Q, Y_Q$

$$\mathcal{M}_t = \begin{pmatrix} \lambda_t \frac{v}{\sqrt{2}} & 0 \\ \kappa^t_\psi \lambda^t_\psi \frac{v}{\sqrt{2}} & M_\psi \end{pmatrix}$$

for $\psi = Q, X_T$

⇒ Similar matrices in the bottom sector

⇒ Mixing very constraint by Higgs couplings and EWPT:

⇒ t' (b') Couple to Higgs through mixing, couplings to W, Z modified

Few decay modes:

$$X_{5/3} \to W^+ t, \qquad t' \to th, tZ, W^+ b, \qquad b' \to bh, bZ, W^- t,$$

$$Y_{-4/3} \to W^- b$$

Production of VLQs

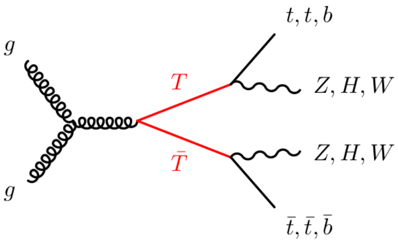
Pair vs single production

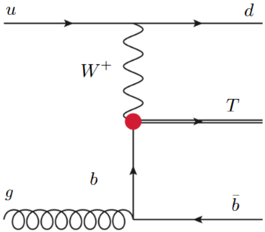
- QCD pair production dominates below 1 *TeV*

$\Rightarrow$ Model independent

- Single production by EW interactions may become relevant at higt mass

$\Rightarrow$ Depends on the mixing





Decays of VLQs into SM particles

Branching ratios for t'

Experimental analyses assume: $Br(t' \to bW^+) + Br(t' \to Zt) + Br(t' \to ht) = 1$, $Br(X \to tW^+) = 1$, similar for b' and Y

Assuming small mixing as experimentally required: $Br(t' \to ht) \simeq Br(t' \to Zt)$

- Singlets: $Br_{Zt} \simeq 1/4$, $Br_{Wb} \simeq 1/2$, (T, X_Q)
- Doublets: $Br_{Zt} \simeq 1/2$, $Br_{Wb} \simeq 0$, (X_T, Y_Q)
- Triplets behave like singlets or doublets
- Doublet Q may behave like singlet or doublets or differently

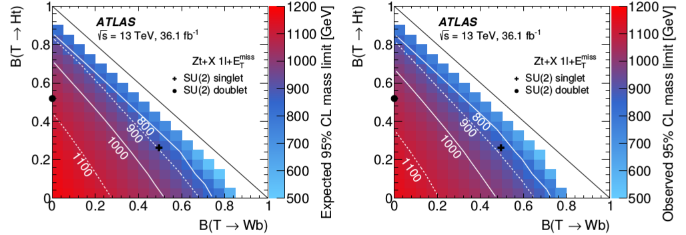


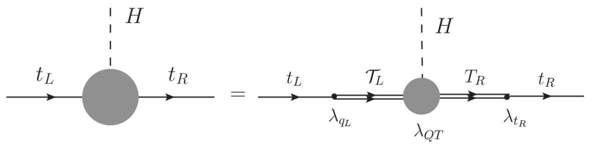
Figure 7: Expected (left) and observed (right) 95% CL lower limit on the T quark mass as a function of the decay branching ratios into Wb and Ht. The markers indicate the branching ratios in the singlet and doublet models for masses above about 0.8 TeV, where they are approximately independent of the T quark mass.

VLQs in CHMs

More complicated situation in realistic CHMs:

- No yukawa couplings associated to elementary fields q_L and t_R

⇒ Top yukawa coupling generated through PC



- Top partners appear in complete multiplets of the global symmetry

⇒ Several top partners: larger mixing matrix

$SU(4) \times SU(6)/Sp(4) \times SO(6)$ example: $\Psi = (\psi\psi X) \sim (6,6)_{SU(4)\times SU(6)}$

$$M_{\text{top}} = \begin{pmatrix} 0 & y_{5L} f \cos^2\frac{\epsilon}{2} & -y_{5L} f \sin^2\frac{\epsilon}{2} & \frac{y_{1L} f}{\sqrt{2}} \sin\epsilon & 0 \\ \frac{y_{5R} f}{\sqrt{2}} \sin\epsilon & M_5 & 0 & 0 & 0 \\ \frac{y_{5R} f}{\sqrt{2}} \sin\epsilon & 0 & M_5 & 0 & 0 \\ y_{1R} f \cos\epsilon & 0 & 0 & M_1 & 0 \\ 0 & 0 & 0 & 0 & M_5 \end{pmatrix}$$

Outlooks for top partners decays

New decay modes

- Top partners:

Possible to have $t' \to \eta_0 t$ with non-negligible branching ratio

- Exotic charges:

- May decay into the additional EW pNGBs such as $X \to t\phi_+$, $X \to b\phi_+^+$ $,\cdots$
- Decays to coloured pNGBs

⇒ Reduce usual branching ratios ie change experimental bounds on VLQs masses

Conclusion

SM theoretical issues:

- Hierarchy poblem ⇒ pNGB Higgs
- Large top mass ⇒ PC

Framework

Stongly coupled hypercolour gauge theory with purely fermionic matter that condenses at low energy (2 species of hyperfermions)

⇒ Fermionic UV completions including PC implies the existence of very specific additional pNGBs that should be accessible at the LHC

Interesting signatures common to all models

- Extended Higgs sector: singlets, doublets, triplets, $\cdots$
- Non-anomalous singlet η_0 (also η')
- Coloured pNGB octet but also triplets or sextets

⇒ First evidence of CHMs may come from discovery of additional pNGBs (di-boson, di-top searches) rather than top partners

- Light top partners with possibly new decay modes linked to the introduction of PC ⇒ Change the experimental bounds on the masses

Composite Higgs models offer a very rich phenomenology that needs to be confronted by collider analyses

Thanks for your attention!