Universitá di Roma Tre, 15 November 2012

Indirect Constraints on Composite Higgs Models

David M. Straub | Johannes Gutenberg University Mainz

in collaboration with R. Barbieri, D. Buttazzo, F. Sala, A. Tesi

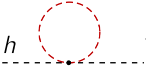
Outline

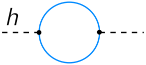
1. **Introduction**: a 125 GeV composite Higgs vs. naturalness
2. Partial compositeness vs. **electroweak precision tests**
3. **Flavour**: anarchy vs. symmetry
   - Anarchy
   - $U(3)^3$
   - $U(2)^3$
4. **Summary**: the natural composite Higgs

The gauge hierarchy problem

Now that we know there is a Higgs, we need to find out whether it is . . .

1. **unnatural** – extreme fine tuning of $O(M_P^2/v^2)$
2. **supersymmetric** – weakly coupled EWSB
3. **composite** – strongly coupled EWSB

$(m_h^2)_{\text{fund}} +$ 

$+$ 

$= (m_h^2)_{\text{phys}}$

The Higgs as a pseudo Goldstone boson

The Higgs as a bound state of a new strong interaction:

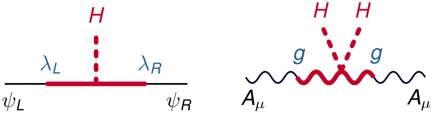
- it should be naturally the lightest resonances: a **pseudo Goldstone boson** of a global symmetry broken at a scale f
- $f > v$ (phenomenologically necessary) requires fine-tuning at least of order f^2/v^2

[Contino 1005.4269, . . .]

Partial compositeness

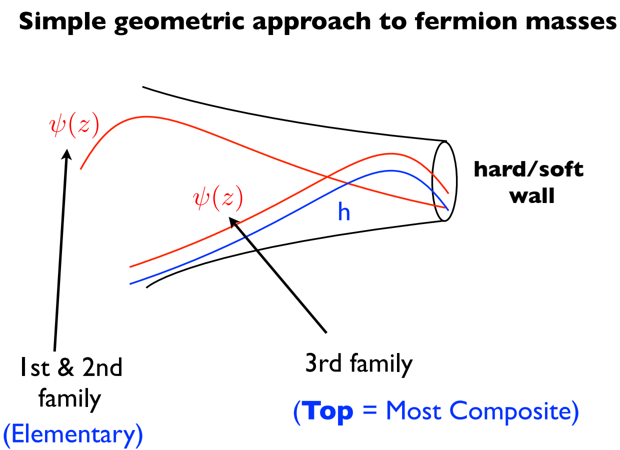
Fundamental massless fermions and gauge bosons mix with composite operators and obtain masses after EWSB

$$\mathcal{L} \supset \lambda_L \bar{\psi}_L \mathcal{O}_R + \lambda_R \bar{\psi}_R \mathcal{O}_L + g A_\mu \mathcal{J}^\mu$$



[Kaplan (1991)]

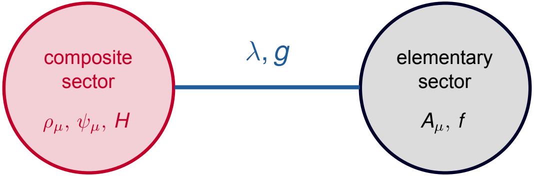
The 5D picture



[Pomarol]

The two-site picture

Consider 1 set of resonances (4D)



- Captures the most relevant phenomenology (in particular for tree-level effects)
- Spin-1 resonances of mass $\sim m_\rho = g_\rho f$
- Spin-$\frac{1}{2}$ resonances of mass $\sim m_\psi = Yf$

[Contino et al. hep-ph/0612180, . . .]

The 125 GeV composite Higgs

Generically, the Higgs mass comes out as

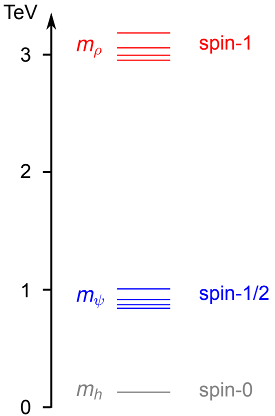
$$m_h = O(1) \times \frac{\sqrt{N_c}}{\pi} m_t Y$$

- Y should be semi-perturbative , $Y \sim 1$–2
- $f^2/v^2 \lesssim 10 \Rightarrow m_\psi = Yf = O(\text{TeV})$

A 125 GeV Higgs requires light fermion resonances!

[Pomarol and Riva 1205.6434, Redi and Tesi 1205.0232, Matsedonskyi et al. 1204.6333, Panico et al. 1210.7114]

The natural composite Higgs



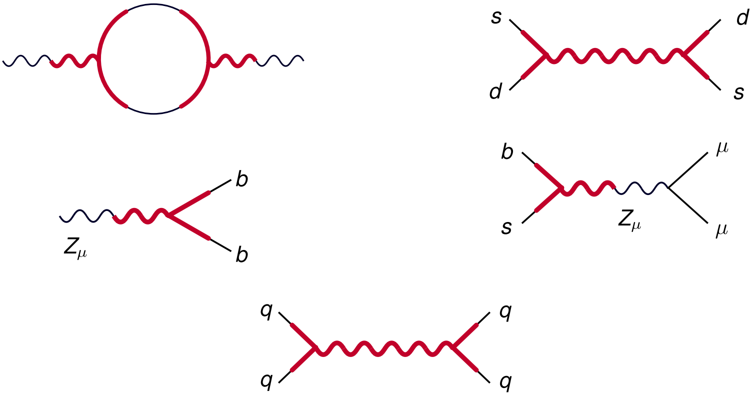
$m_\rho \gtrsim 2.8$ TeV required by S parameter

$m_\psi \lesssim 1$ TeV preferred by naturalness

LHC direct bounds: $m_\psi \gtrsim 500$–600 GeV

Indirect constraints on partial compositeness

Composite/elementary mixing produces corrections to electroweak and flavour precision observables starting at tree level



Outline

1. **Introduction**: a 125 GeV composite Higgs vs. naturalness
2. Partial compositeness vs. **electroweak precision tests**
3. **Flavour**: anarchy vs. symmetry
   - Anarchy
   - $U(3)^3$
   - $U(2)^3$
4. **Summary**: the natural composite Higgs

Custodial symmetry

The vector resonances transform as adjoints under a group $G \supset G_{SM}$. To protect the T parameter from tree-level contributions, G has to contain

$$G_c = SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X$$
$$Y = T_{3R} + X$$

Custodial symmetry

The vector resonances transform as adjoints under a group $G \supset G_{\mathrm{SM}}$. To protect the T parameter from tree-level contributions, G has to contain

$$G_c = SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X$$
$$Y = T_{3R} + X$$

We consider three choices for the composite fermion representations under G_c:

	q_L couples to ...
doublet model	$(2,1)$
triplet model	$(1,3)$
bidoublet model	$(2,2)+(2,2)$
	...of $SU(2)_L \times SU(2)_R$

Setup: the doublet model

	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_X$
Q	**3**	**2**	**1**	$\frac{1}{6}$
$R = (U \;\; D)$	**3**	**1**	**2**	$\frac{1}{6}$

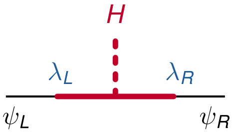
$$\mathcal{L}_s^{\text{doublet}} = -\bar{Q}^i m_Q^i Q^i - \bar{R}^i m_R^i R^i + \left(Y^{ij} \text{tr}[\bar{Q}_L^i \mathcal{H} R_R^j] + \text{h.c} \right)$$

$$\mathcal{L}_{\text{mix}}^{\text{doublet}} = m_Q^j \lambda_L^{ij} \bar{q}_L^i Q_R^j + m_R^j \lambda_{Ru}^{ij} \bar{U}_L^i u_R^j + m_R^j \lambda_{Rd}^{ij} \bar{D}_L^i d_R^j$$

NB: the right mixings break custodial symmetry

Yukawas

$$\mathcal{L}_{\text{mix}}^{\text{doublet}} = m_Q^j \lambda_L^{ij} \bar{q}_L^i Q_R^j + m_R^i \lambda_{Ru}^{ij} \bar{U}_L^i u_R^j + m_R^i \lambda_{Rd}^{ij} \bar{D}_L^i d_R^j$$



$$y_{u_i} = Y s_{Li} s_{Rui} \qquad y_{d_i} = Y s_{Li} s_{Rdi} \qquad s_X = \frac{\lambda_X}{\sqrt{1+\lambda_X{}^2}}$$

The large top Yukawa requires considerably composite tops:

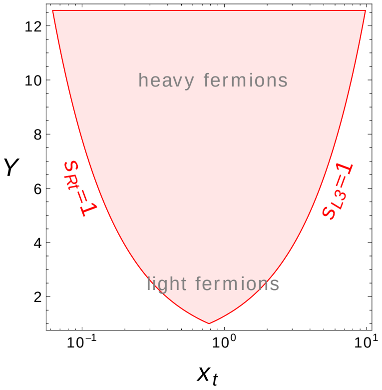
$$y_t = Y s_{L3} s_{Rt} \sim 1$$

A useful parametrization

$$x_t \equiv \frac{s_{L3}}{s_{Rt}}$$

$$y_t = Y s_{L3} s_{Rt} \sim 1$$

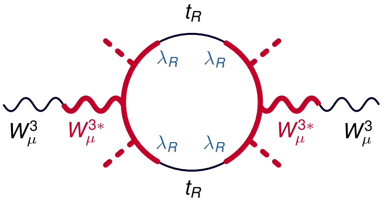
$$\Rightarrow \frac{y_t}{Y} < x_t < y_t Y$$



$$s_{L3} s_{Rt,b} = \frac{y_{t,b}}{Y} \qquad s_{L3}^2 = \frac{x_t y_t}{Y} \qquad s_{Rt}^2 = \frac{y_t}{x_t Y} \qquad s_{Rb}^2 = \frac{y_t}{x_t Y} \frac{y_b^2}{y_t^2}$$

The T parameter in the doublet model

The right mixings break custodial symmetry $\Rightarrow$ 1-loop contribution to T, e.g.



For small mixing, we find

$$\alpha T = \frac{71}{140} \frac{N_c}{16\pi^2} \frac{m_t^2}{m_\psi^2} \frac{Y^2}{x_t^2}$$

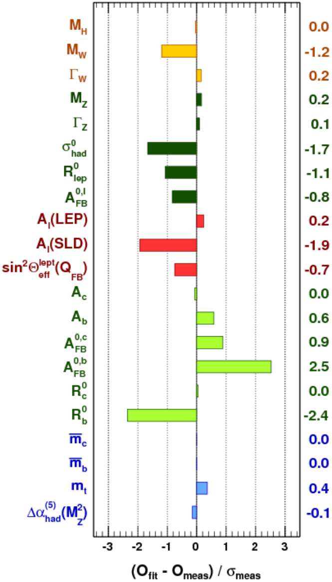
$$T - T_{\text{SM}} = 0.05 \pm 0.12 \Rightarrow m_\psi > 0.3 \left(Y/x_t \right) \text{TeV}$$

$Z \to b\bar{b}$

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to q\bar{q})}$$

$$R_b^{\text{exp}} = 0.21629(66)$$
$$R_b^{\text{SM}} = 0.21474(3)$$

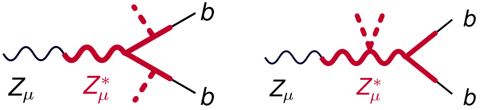
2.4σ discrepancy [Baak et al. 1209.2716]



$Z \to b\bar{b}$

Z coupling to fermions corrected due to fermion and gauge boson mixing:

$$\delta g^L_{Zbb} = \frac{v^2 Y^2}{4m_R^2}\frac{xy_t}{Y} + \frac{g_\rho^2 v^2}{8m_\rho^2}\frac{xy_t}{Y}$$



The correction goes in the wrong direction . . .

$$m_\rho = g_\rho f\,,\ m_\psi = Yf \ \Rightarrow m_\psi > 5.6\sqrt{x_t Y}\ \text{TeV}$$

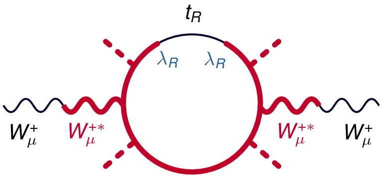
Setup: the triplet model

	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_X$
$L = (Q \;\; Q')$	**3**	**2**	**2**	$\frac{2}{3}$
$R = (X \;\; U \;\; D)^T$	**3**	**1**	**3**	$\frac{2}{3}$
R'	**3**	**3**	**1**	$\frac{2}{3}$

$$\mathcal{L}_s^{\text{triplet}} = -\text{tr}[\bar{L}^i m_L^i L^i] - \text{tr}[\bar{R}^i m_R^i R^i] + \left(Y^{ij} \text{tr}[\bar{L}_L^i \mathcal{H} R_R^j] + \text{h.c} \right)$$

$$\mathcal{L}_{\text{mix}}^{\text{triplet}} = m_L^j \lambda_L^{ij} \bar{q}_L^i Q_R^j + m_R^i \lambda_{Ru}^{ij} \bar{U}_L^i u_R^j + m_R^i \lambda_{Rd}^{ij} \bar{D}_L^i d_R^j$$

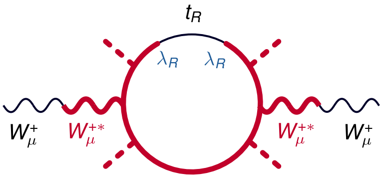
T and R_b in the triplet model



$$\alpha T = \left(\log\frac{\Lambda^2}{m_\psi^2} - \frac{1}{2}\right)\frac{N_c}{16\pi^2}\frac{m_t^2}{m_\psi^2}\frac{Y^3}{y_t x_t}\,, \quad \text{and} \quad \alpha T = \frac{197}{84}\frac{N_c}{16\pi^2}\frac{m_t^2}{m_\psi^2}x_t^2 Y^2\,,$$

$$\Rightarrow m_\psi > 0.5\sqrt{Y^3/x_t}\ \text{TeV} \qquad \Rightarrow m_\psi > 0.6\,(x_t Y)\ \text{TeV}$$

T and R_b in the triplet model



$$\alpha T = \left(\log\frac{\Lambda^2}{m_\psi^2} - \frac{1}{2}\right)\frac{N_c}{16\pi^2}\frac{m_t^2}{m_\psi^2}\frac{Y^3}{y_t x_t}\,, \quad \text{and} \quad \alpha T = \frac{197}{84}\frac{N_c}{16\pi^2}\frac{m_t^2}{m_\psi^2}x_t^2 Y^2\,,$$

$$\Rightarrow m_\psi > 0.5\sqrt{Y^3/x_t}\ \text{TeV} \qquad \Rightarrow m_\psi > 0.6\,(x_t Y)\ \text{TeV}$$

The tree-level correction to $Z \to b_L \bar{b}_L$ vanishes due to LR symmetry

Setup: the bidoublet model

	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_X$
$L_U = (Q_u \;\; Q'_u)$	**3**	**2**	**2**	$\frac{2}{3}$
$L_D = (Q'_d \;\; Q_d)$	**3**	**2**	**2**	$-\frac{1}{3}$
U	**3**	**1**	**1**	$\frac{2}{3}$
D	**3**	**1**	**1**	$-\frac{1}{3}$

$$\mathcal{L}_s^{\text{bidoublet}} = -\text{tr}[\bar{L}_U^i m_{Q_u}^i L_U^i] - \bar{U}^i m_U^i U^i + \left(Y_U^{ij} \text{tr}[\bar{L}_U^i \mathcal{H}]_L U_R^j] + \text{h.c} \right) + (U, u \to D, d)$$

$$\mathcal{L}_{\text{mix}}^{\text{bidoublet}} = m_{Q_u} \lambda_{Lu}^{ij} \bar{q}_L^i Q_{Ru}^j + m_U \lambda_{Ru}^{ij} \bar{U}_L^i u_R^j + (U, u \to D, d) \,,$$

Yukawas in the bidoublet model

The fundamental quark doublet q now couples to two composite fields $Q_{u,d}$

$$y_t = Y s_{Lt} s_{Rt} \sim 1 \qquad y_b = Y s_{Lb} s_{Rt} \sim 1$$

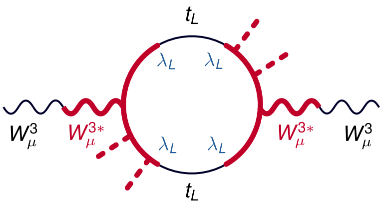
Define again

$$x_t \equiv \frac{s_{Lt}}{s_{Rt}}$$

and now also

$$z = \frac{s_{Lt}}{s_{Lb}} > 1$$

T in the bidoublet model



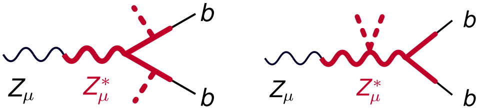
$$\alpha T = -\frac{107}{420}\frac{N_c}{16\pi^2}\frac{m_t^2}{m_\psi^2}x_t^2 Y_U^2 \,.$$

$$\Rightarrow m_\psi > 0.25\,(x_t Y)\ \text{TeV}$$

$Z \to b\bar{b}$ in the bidoublet model

The left-handed coupling has a custodial protection due to the LR symmetry of the model only broken by down-type mixings [Agashe et al. hep-ph/0605341]

$$\delta g^L_{Zbb} = \frac{v^2 Y_D^2}{4 m_D^2} \frac{x y_t}{Y} \frac{1}{z^2} + \frac{g_\rho^2 v^2}{4 m_\rho^2} \frac{x y_t}{Y} \frac{1}{z^2}$$



Again, the wrong direction . . .

$$\Rightarrow m_\psi > 6.5 \sqrt{x_t Y}/z \text{ TeV}$$

Summary: electroweak precision bounds

Lower bounds on m_ψ in TeV

	doublet	triplet	bidoublet
T	$0.28\ Y/x_t$	$0.45\sqrt{Y^3/x_t}$, $0.60\ x_t Y$	$0.25\ x_t Y$
R_b	$5.6\sqrt{x_t Y}$		$6.5\sqrt{x_t Y}/z$
	problematic	OK for small Y	OK for sizable z

Recall: $x_t Y$, $Y/x_t > y_t$, $z > 1$

Outline

1. **Introduction**: a 125 GeV composite Higgs vs. naturalness
2. Partial compositeness vs. **electroweak precision tests**
3. **Flavour**: anarchy vs. symmetry
   - Anarchy
   - $U(3)^3$
   - $U(2)^3$
4. **Summary**: the natural composite Higgs

Anarchy

- Structureless ("anarchic") composite Yukawas

$$\mathcal{L}_s = -\bar{Q}^i m_Q^i Q^i - \bar{R}^i m_R^i R^i + \left(Y^{ij} \text{tr}[\bar{Q}_L^i \mathcal{H} R_R^j] + \text{h.c} \right)$$

- Hierarchies in quark masses and mixing generated by hierarchical composite-elementary mixing

$$\mathcal{L}_{\text{mix}} = m_Q^j \lambda_L^i \bar{q}_L^i Q_R^i + m_R^i \lambda_{Ru}^i \bar{U}_L^i u_R^i + m_R^i \lambda_{Rd}^i \bar{D}_L^i d_R^i$$

An attractive mechanism to explain the origin of quark mass and mixing hierarchies

[Grossman and Neubert hep-ph/9912408, Gherghetta and Pomarol hep-ph/0003129, Huber and Shafi hep-ph/0010195, Agashe et al. hep-ph/0412089, . . .]

Quark masses and mixings from anarchy

$$y_{u_i} \sim Y_* s_{Li} s_{Rui}$$

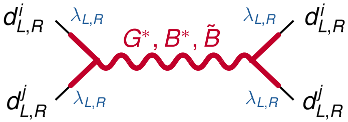
$$s_{L3} \gg s_{L2} \gg s_{L1}$$

$$s_{Ru3} \gg s_{Ru2} \gg s_{Ru1}$$

$$V_{\text{CKM}}^{ij} \sim \frac{s_{Li}}{s_{Lj}}$$

- All mixings determined by masses and CKM up to $O(1)$ factors
  - only free parameter: x_t (bidoublet model: also z)

Anarchic FCNCs



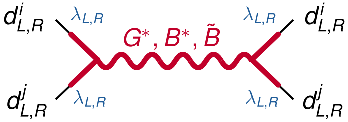
Relation between c.-el. mixings and quark masses & CKM leads to a suppression of FCNCs:

$$s_{Li}^2 s_{Lj}^2 \sim (V_{3i}^* V_{3j}^*)^2 \left(\frac{x_t y_t}{Y}\right)^2$$

almost "$O(1) \times$ MFV" . . . **but** also RR and LR FCNCs

$$s_{Li}^2 s_{Rj}^2 \sim y_{di} y_{dj}$$

Anarchic FCNC operators



$$Q_V^{AB} = (\bar{d}^i_A \gamma^\mu d^j_A)(\bar{d}^i_B \gamma^\mu d^j_B) \qquad Q_S^{LR} = (\bar{d}^i_R d^j_L)(\bar{d}^i_L d^j_R)$$

General structure of the contributions:

$$C_V^{LL} \propto \frac{g_\rho^2}{m_\rho^2}\left(\frac{x_t}{Y}\right)^2 = \left(\frac{x_t}{m_\psi}\right)^2 \qquad C_V^{RR} \propto \frac{g_\rho^2}{m_\rho^2}\left(\frac{1}{x_t Y}\right)^2 = \left(\frac{1}{x_t m_\psi}\right)^2 \qquad C_{V,S}^{LR} \propto \frac{g_\rho^2}{m_\rho^2}\left(\frac{1}{x_t Y}\right)^2 = \left(\frac{1}{m_\psi}\right)^2$$

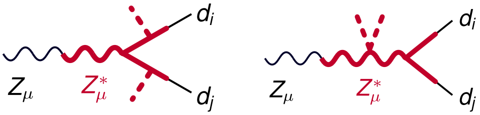
Anarchic $\Delta F = 2$ bounds

	doublet	triplet	bidoublet
$\epsilon_K \; (Q_S^{LR})$	14	14	14 z
$\epsilon_K \; (Q_V^{LL})$	2.7 x_t	3.9 x_t	3.9 x_t
B-$\bar{B}$	2.3 x_t	3.4 x_t	3.4 x_t
B_s-$\bar{B}_s$	2.3 x_t	3.4 x_t	3.4 x_t
D-$\bar{D} \; (Q_S^{LR})$	0.5	0.5	0.5
D-$\bar{D} \; (Q_V^{LL})$	0.4 x_t	0.6 x_t	0.6 x_t

- Q_S^{LR} contribution to ϵ_K highly problematic
- Otherwise, OK for smallish x_t

using bounds in [Isidori et al. 1111.4987, Calibbi et al. 1204.1275]

Flavour-changing Z couplings



$$\delta g^{L,R}_{Zd^i d^j} \sim \frac{s_{L,Rdi} s_{L,Rdj}}{s^2_{L,Rb}} \delta g^{L,R}_{Zbb}$$

- For the LH coupling, bounds from $K_L \to \mu^+\mu^-$, $B_s \to \mu^+\mu^-$ are comparable to R_b
- For the RH coupling $K_L \to \mu^+\mu^-$ bound is the strongest:

	doublet	triplet	bidoublet
$K_L \to \mu\mu$	$0.56\sqrt{Y/x_t}$	$0.56\sqrt{Y/x_t}$	

Summary: anarchy

The most significant bounds on m_ψ:

	doublet	triplet	bidoublet
T	$0.28\ Y/x_t$	$0.45\ \sqrt{Y^3/x_t}$, $0.60\ x_t Y$	$0.25\ x_t Y$
R_b	$5.6\ \sqrt{x_t Y}$		$6.5\ \sqrt{x_t Y}/z$
$\epsilon_K\ (Q_S^{LR})$	14	14	$14\ z$
$\epsilon_K\ (Q_V^{LL})$	$2.7\ x_t$	$3.9\ x_t$	$3.9\ x_t$

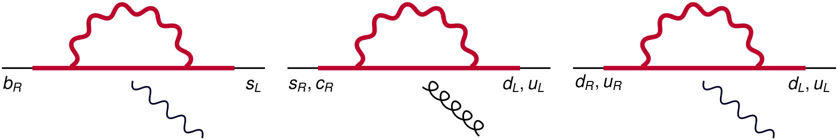
Hoping for a fortuitous cancellation in Q_S^{LR} and forgetting about the doublet model: $x_t \sim 1/3 \Rightarrow Y \sim 2.5 \Rightarrow m_\psi \sim 1.2$ TeV

Comment on loops

- Loop-induced FCNC dipole operators and electric dipole moments also lead to relevant constraints
- Slightly more model dependent, but generically lead to

$$m_\psi > O(\text{TeV}) \times Y$$

  Additional motivation for small Y!
- Main players: $b \to s\gamma$, ϵ'/ϵ, ΔA_{CP}, d_n



see e.g. [Agashe et al. hep-ph/0408134, Agashe et al. 0810.1016, Vignaroli 1204.0478, ...]

Outline

1. **Introduction**: a 125 GeV composite Higgs vs. naturalness
2. Partial compositeness vs. **electroweak precision tests**
3. **Flavour**: anarchy vs. symmetry
   - Anarchy
   - $U(3)^3$
   - $U(2)^3$
4. **Summary**: the natural composite Higgs

$U(3)^3$: the MFV composite Higgs

- Solve the anarchic flavour problem by imposing MFV
  - Give up the anarchic solution to the flavour puzzle
- Strong sector assumed flavour blind
  - Mass hierarchies and CKM generated by comp.-el. mixings
- Two options: left- and right-compositeness

[Cacciapaglia et al. 0709.1714, Redi and Weiler 1106.6357, Redi 1203.4220]

$U(3)^3$ left-compositeness

- the strong sector possesses a $U(3)_{U+D}$ symmetry
- the right mixings are the only spurions breaking $U(3)_{q+U+D} \times U(3)_u \times U(3)_d$

$$\mathcal{L}_{\text{mix}}^{\text{doublet}} = m_Q^j \lambda_L^{ij} \bar{q}_L^i Q_R^j + m_R^i \lambda_{Ru}^{ij} \bar{U}_L^i u_R^j + m_R^i \lambda_{Rd}^{ij} \bar{D}_L^i d_R^j$$

$$\lambda_L \propto \mathbb{1}$$

$$\lambda_{Ru} \propto V_{\text{CKM}}^\dagger Y_u$$

$$\lambda_{Rd} \propto Y_d$$

$U(3)^3$ right-compositeness

- the strong sector possesses a $U(3)_U \times U(3)_D$ symmetry
- the left mixings are the only spurions breaking $U(3)_q \times U(3)_{u+U} \times U(3)_{d+D}$
- only possible in bidoublet model ($\lambda_{Lu} \neq \lambda_{Ld}$)

$$\mathcal{L}_{\text{mix}}^{\text{bidoublet}} = m_{Q_u} \lambda_{Lu}^{ij} \bar{q}_L^i Q_{Ru}^j + m_U \lambda_{Ru}^{ij} \bar{U}_L^i u_R^j + (U, u \to D, d)$$

$$\lambda_{Lu} \propto V_{\text{CKM}}^\dagger Y_u$$
$$\lambda_{Ld} \propto Y_d$$
$$\lambda_{Ru,d} \propto \mathbb{1}$$

Implications of $U(3)^3$

Light quark compositeness

Since in $U(3)^3_{\text{LC}}$ and $U(2)^3_{\text{RC}}$

$$\lambda_L \propto \mathbb{1} \qquad \text{or} \qquad \lambda_{Ru,d} \propto \mathbb{1}$$

Not only the top but also (left- or right handed) light quarks are strongly composite!

Flavour gauge bosons

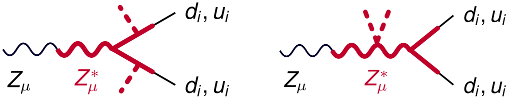
Expect vector resonances associated to the global $U(3)$ ($U(3)^2$) flavour symmetry in the strong sector

$U(3)^3_{\mathrm{LC}}$ worsens electroweak precision observables

Hadronic width:

$$R_h = \frac{\Gamma(Z \to qq)}{\Gamma(Z \to \mu\mu)}$$

all generations, both up and down contribute. Custodial protection in the bidoublet model inactive.

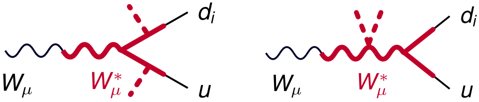


	doublet	triplet	bidoublet
R_h	$4.3\sqrt{x_t Y}$	$6.0\sqrt{x_t Y}$	$4.9\sqrt{x_t Y}$

$U(3)^3_{\mathrm{LC}}$ worsens electroweak precision observables

First row CKM unitarity

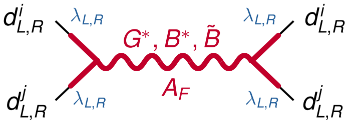
$$\sum_i |V_{ui}|^2 - 1 = (-1 \pm 6) \times 10^{-4}$$



	doublet	triplet	bidoublet
R_h	$4.3\sqrt{x_t Y}$	$6.0\sqrt{x_t Y}$	$4.9\sqrt{x_t Y}$
V_{CKM}	$5.2\sqrt{x_t Y}$	$5.2\sqrt{x_t Y}$	$4.3\sqrt{x_t Y}$

$U(3)^3$ FCNCs

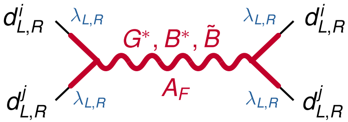
- In $U(3)^3_{LC}$, there are no FCNCs at tree level [Redi and Weiler 1106.6357]
- In $U(3)^3_{RC}$, there are MFV FCNCs [Barbieri et al. 1203.4218]



	bidoublet
ϵ_K	3.3 x_t
B_d-$\bar{B}_d$	2.8 x_t
B_s-$\bar{B}_s$	3.1 x_t

$U(3)^3$ FCNCs

- In $U(3)^3_{\text{LC}}$, there are no FCNCs at tree level [Redi and Weiler 1106.6357]
- In $U(3)^3_{\text{RC}}$, there are MFV FCNCs [Barbieri et al. 1203.4218]

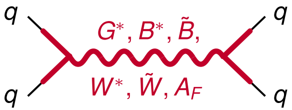


	bidoublet
ϵ_K	$3.3\ x_t$
B_d-$\bar{B}_d$	$2.8\ x_t$
B_s-$\bar{B}_s$	$3.1\ x_t$

NB: $O(1)$ uncertainties of anarchic FCNCs are absent here! Everything fixed in terms of masses, CKM

Compositeness constraints

First generation quarks have a sizable degree of compositeness



$\Rightarrow$ 4-fermion operators that modify the angular distribution of $pp \to jj$ @LHC

$U(3)^3_{\text{LC}}$

$$(\bar{q}_L \gamma^\mu q_L)(\bar{q}_L \gamma_\mu q_L)$$
$$(\bar{q}_L \gamma^\mu T^a q_L)(\bar{q}_L \gamma_\mu T^a q_L)$$

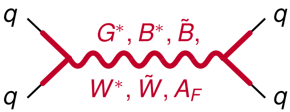
[Domenech et al. 1201.6510]

$U(3)^3_{\text{RC}}$

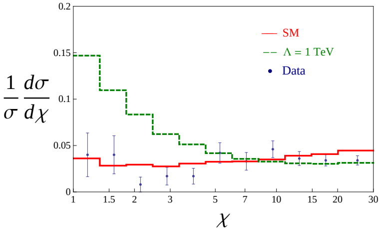
$$(\bar{u}_R \gamma^\mu u_R)(\bar{u}_R \gamma_\mu u_R)$$
$$(\bar{d}_R \gamma^\mu d_R)(\bar{d}_R \gamma_\mu d_R)$$
$$(\bar{u}_R \gamma^\mu u_R)(\bar{d}_R \gamma_\mu d_R)$$
$$(\bar{u}_R \gamma^\mu T^a u_R)(\bar{d}_R \gamma_\mu T^a d_R)$$

Compositeness constraints

First generation quarks have a sizable degree of compositeness



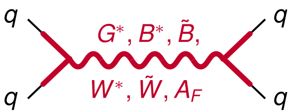
$\Rightarrow$ 4-fermion operators that modify the angular distribution of $pp \to jj$ @LHC



[Domenech et al. 1201.6510]

Compositeness constraints

First generation quarks have a sizable degree of compositeness



$\Rightarrow$ 4-fermion operators that modify the angular distribution of $pp \to jj$ @LHC

	doublet	triplet	bidoublet
$U(3)^3_{\text{LC}}$	$3.4\ x_t$	$4.2\ x_t$	$4.2\ x_t$
$U(3)^3_{\text{RC}}$			$3.0/x_t$

$U(3)^3$ summary

- In $U(3)^3_{\text{LC}}$, EWPT alone require $m_\psi \gtrsim 4$ TeV

	doublet	triplet	bidoublet
R_h	$4.3\sqrt{x_t Y}$	$6.0\sqrt{x_t Y}$	$4.9\sqrt{x_t Y}$

- In $U(3)^3_{\text{RC}}$, flavour vs. collider requires $m_\psi \gtrsim 3$ TeV

	bidoublet
ϵ_K	$3.3\, x_t$
$pp \to jj$	$3.0/x_t$

Outline

1. **Introduction**: a 125 GeV composite Higgs vs. naturalness
2. Partial compositeness vs. **electroweak precision tests**
3. **Flavour**: anarchy vs. symmetry
   - Anarchy
   - $U(3)^3$
   - $U(2)^3$
4. **Summary**: the natural composite Higgs

$U(2)^3$

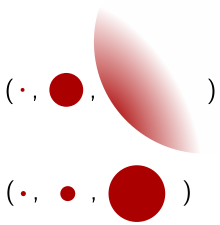
The SM quark sector is approximately invariant under

$$U(2)^3 = U(2)_Q \times U(2)_U \times U(2)_D$$

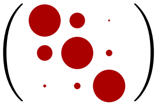
with the first two generations transforming as doublet, the 3rd as singlet

$(m_u, m_c, m_t) \sim$

$(m_d, m_s, m_b) \sim$



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



Impose $U(2)^3$ and break it *weakly* and *minimally*

General consequences of minimally broken $U(2)^3$

- FCNC protection comparable to MFV = $U(3)^3$, **but**
- Universal CPV phase in B_d and B_s mixing
- More phases in $\Delta F = 1$ processes
- MFV correlations between K and $B_{d,s}$ systems broken

[Barbieri et al. 1203.4218, Barbieri et al. 1206.1327, Buras and Girrbach 1206.3878]

General consequences of minimally broken $U(2)^3$

- FCNC protection comparable to MFV = $U(3)^3$, **but**
- Universal CPV phase in B_d and B_s mixing
- More phases in $\Delta F = 1$ processes
- MFV correlations between K and $B_{d,s}$ systems broken

[Barbieri et al. 1203.4218, Barbieri et al. 1206.1327, Buras and Girrbach 1206.3878]

Original motivation: natural SUSY [Barbieri et al. 1105.2296, . . .]

$U(2)^3$ and partial compositeness

$U(2)^3$ left- and right compositeness:

- The strong sector posssesses a $U(2)$ ($U(2)^2$) symmetry
- mass and CKM hierarchies generated by comp.-el. mixings

$$U(2)^3_{\text{LC(RC)}} : \lambda_{L(R)} \propto \begin{pmatrix} \epsilon & & \\ & \epsilon & \\ & & 1 \end{pmatrix}$$

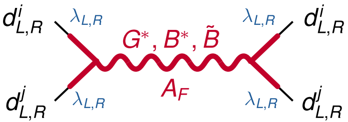
No connection between the 1st and 3rd generations

- $U(3)^3$ problems cured!
- EWP constaints as in anarchy

$U(2)^3_{\text{RC}}$ FCNCs

In $U(3)^3_{\text{RC}}$ (bidoublet) FCNCs are MFV like in $U(3)^3_{\text{RC}}$

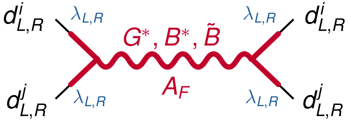
- No phase in $\Delta F = 2$
- Correlation between K and $B_{d,s}$ present



$U(2)^3_{\text{RC}}$	bidoublet
ϵ_K	$3.9\ x_t$
B-$\bar{B}$	$3.4\ x_t$
B_s-$\bar{B}_s$	$3.4\ x_t$

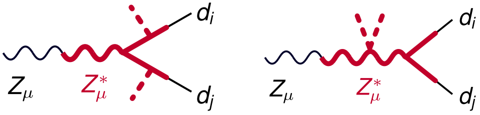
$U(2)^3_{\mathrm{LC}}$ FCNCs

- New phase in $B_{d,s}$ mixing
- Correlation between $s \leftrightarrow d$ and $b \leftrightarrow s, d$ broken



$U(2)^3_{\mathrm{LC}}$	doublet	bidoublet	triplet
ϵ_K	$2.1\ x_t \lvert r_b \rvert^2$	$3.5\ x_t \lvert r_b \rvert^2$	$3.5\ x_t \lvert r_b \rvert^2$
B-$\bar{B}$	$1.8\ x_t \lvert r_b \rvert$	$3.0\ x_t \lvert r_b \rvert$	$3.0\ x_t \lvert r_b \rvert$
B_s-$\bar{B}_s$	$1.8\ x_t \lvert r_b \rvert$	$3.0\ x_t \lvert r_b \rvert$	$3.0\ x_t \lvert r_b \rvert$

$U(2)^3_{\mathrm{LC}}$ flavour-changing Z couplings



	doublet	triplet	bidoublet
$K_L \to \mu\mu$	$3.8\,\sqrt{x_t Y}\lvert r_b\rvert$	–	$3.8\,Y_D\lvert r_b\rvert\sqrt{x_t/Y_U}/z$
$b \to s\ell\ell$	$3.5\,\sqrt{x_t Y\lvert r_b\rvert}$	–	$3.5\,Y_D\sqrt{x_t\lvert r_b\rvert/Y_U}/z$

Comparable to R_b unless $\lvert r_b\rvert < 1$

$U(2)^3$ summary

- $U(2)^3_{\text{LC}}$ can accomodate $m_\psi <$ TeV for $Y \sim 1$, $r_b \sim 0.2$
  (apart from the doublet case which has an R_b problem)

	doublet	triplet	bidoublet
T	$0.28\ Y/x_t$	$0.45\sqrt{Y^3/x_t}$, $0.60\ x_t Y$	$0.25\ x_t Y$
R_b	$5.6\sqrt{x_t Y}$		$6.5\sqrt{x_t Y}/z$
$B_{d,s}$-$\bar{B}_{d,s}$	$1.8\ x_t\|r_b\|$	$3.0\ x_t\|r_b\|$	$3.0\ x_t\|r_b\|$

- $U(2)^3_{\text{RC}}$ can have $m_\psi \sim 1.2$ TeV, but at the price of $x_t \lesssim 0.3 \Rightarrow Y \gtrsim 2.5$

	bidoublet
ϵ_K	$3.9\ x_t$

Outline

1. **Introduction**: a 125 GeV composite Higgs vs. naturalness

2. Partial compositeness vs. **electroweak precision tests**

3. **Flavour**: anarchy vs. symmetry
   - Anarchy
   - $U(3)^3$
   - $U(2)^3$

4. **Summary**: the natural composite Higgs

How light can the fermion resonances be?

Under the most favourable circumstances (and ignoring the $\Delta S = 2$ LR operator), m_ψ in TeV is at least

	doublet	triplet	bidoublet
Ⓐ	4.9	1.7	1.2∗
$U(3)^3_{\text{LC}}$	3.8	5.3	4.3
$U(3)^3_{\text{RC}}$			3.1
$U(2)^3_{\text{LC}}$	4.9	0.5	0.6
$U(2)^3_{\text{RC}}$			1.2∗

∗ $Y \gtrsim 2.5$

Where could new effects show up?

	Ⓐ	$U(3)^3_{\text{LC}}$	$U(3)^3_{\text{RC}}$	$U(2)^3_{\text{LC}}$	$U(2)^3_{\text{RC}}$	
$\epsilon_K, \Delta M_{d,s}$	★	○	★	★	★	L
$\Delta M_s/\Delta M_d$	★	○	○	○	○	L
$\phi_{d,s}$	★	○	○	★	○	F
$\phi_s - \phi_d$	★	○	○	○	○	F
C_{10}	★	○	○	★	○	F
C'_{10}	★	○	○	○	○	F
$pp \to jj$	○	★	★	○	○	C
$pp \to q'q'$	★	○	○	★	★	C

Conclusions

1. Bounds on natural CHM are dominated by **indirect tests** (flavour, EWPT, compositeness) even with large flavour symmetries
2. A natural 125 GeV composite Higgs can be in agreement with all bounds. Most attractive: $\boldsymbol{U(2)^3_{\mathrm{LC}}}$ triplet or bidoublet.

   Predictions:
   - Fermion resonance pair production at LHC
   - Flavour signals possible, e.g. in:
     ϕ_s, $|\epsilon_K|$, $B_s \to \mu\mu$, $B \to X_s\gamma$, ϵ'/ϵ, ΔA_{CP}, ...