Composite Higgs Models in the LHC Era



Michele Redi

OUTLINE

OUTLINE

- Standard Model Higgs
- Higgs as Nambu-Goldstone boson
- Realizations in 4d and 5d
- EWPT, flavor and LHC searches
- Higgs potential

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 $m_h \approx 125 \,\mathrm{GeV}$

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What is the nature of the Higgs particle?

Mass for gauge bosons means new degrees of freedom



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Nambu-Goldstone Bosons

 $SU(2)_L \otimes U(1)_Y \to U(1)_Q$

become longitudinal polarizations of W & Z

Custodial symmetry

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} \approx 1 \qquad \longrightarrow \qquad SU(2)_c$$

In SM electro-weak symmetry broken by scalar doublet



$$V(H) = \lambda \left(|H|^2 - v^2 \right)^2$$

$$H(x) = U(x) \left(\begin{array}{c} 0\\ \frac{v+h(x)}{\sqrt{2}} \end{array}\right)$$

 $v = 246 \,\mathrm{GeV}$

$$\frac{SU(2)_L \otimes SU(2)_R}{SU(2)_{L+R}} \longrightarrow \rho \approx 1$$

Physical scalar is the Higgs boson $m_h = \sqrt{\lambda} v$

In principle Higgs scalar not even needed



$$A(W_L^+ W_L^- \to W_L^+ W_L^-) = \frac{1}{v^2} (s+t)$$

$$\mathcal{L} = \frac{v^2}{4} \operatorname{Tr} \left[\partial_{\mu} U \partial^{\mu} U^{\dagger} \right] = \frac{1}{2} \left(1 - \frac{\pi^i \pi^i}{v^2} + \dots \right) \partial_{\mu} \pi^i \partial^{\mu} \pi^i$$

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New physics must appear below

$$\Lambda = 4\pi v \sim 3 \text{TeV}$$

QCD breaks electro-weak symmetry

$$<\bar{\Psi}_{L}^{i}\Psi_{R}^{j}>=\Lambda_{QCD}^{3}\,\delta_{ij} \longrightarrow \frac{SU(2)_{L}\otimes SU(2)_{R}}{SU(2)_{L+R}} \longrightarrow \mathcal{L}=f_{\pi}^{2}\,Tr\left[\partial_{\mu}U\partial^{\mu}U^{\dagger}\right]$$

QCD breaks electro-weak symmetry

 $\langle \bar{\Psi}_{L}^{i}\Psi_{R}^{j} \rangle = \Lambda_{QCD}^{3} \delta_{ij} \longrightarrow \frac{SU(2)_{L} \otimes SU(2)_{R}}{SU(2)_{L+R}} \longrightarrow \mathcal{L} = f_{\pi}^{2} Tr \left[\partial_{\mu}U\partial^{\mu}U^{\dagger}\right]$

Technicolor is a rescaled version of QCD f=v. No Higgs scalar but techni-resonances (spin 0, 1/2, 1, ... etc.).

 $----- m_{
ho} < 3 \,\mathrm{TeV}$

 $m_W = 80 \,\mathrm{GeV}$

Ruled out.

In the SM:





$$A(W_L^+ W_L^- \to W_L^+ W_L^-) \simeq \left[s - a^2 \frac{s^2}{s - m_h^2} + (s \to t)\right]$$

Amplitude goes to constant if a=I

$$\mu \frac{d\lambda}{d\mu} = \frac{1}{16\pi^2} (24\lambda^2 - 6y_t^4 + \dots)$$





 $115\,\mathrm{GeV} < m_h < 160\,\mathrm{GeV}$

With 125 GeV Higgs SM can be valid up Mp.

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HIERARCHY PROBLEM

SM is an effective theory valid up to $\,\Lambda\,$

$$\mathcal{L} = \mathcal{L}_{kin} + g A_{\mu} \bar{\psi} \gamma^{\mu} \psi + y \bar{\psi} H \psi - \lambda |H|^4 \qquad D = 4$$

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Irrelevant interactions:

$$\frac{1}{\Lambda} (lH^c)^2 \qquad \frac{1}{\Lambda^2} (\bar{\psi}\psi)^2 \qquad \frac{1}{\Lambda} \bar{\psi} \,\sigma^{\mu\nu} \psi F_{\mu\nu} \qquad D > 4$$

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One relevant operator

$$[H^2] \approx 2 \qquad \qquad m_h \sim \Lambda$$

Perturbatively:



$$\delta m_h^2 = -\frac{3\lambda_t^2}{8\pi^2}\Lambda_t^2 \qquad \longrightarrow \qquad \Lambda_t \sim 3\,m_h$$



$$\delta m_h^2 = \frac{9g^2 + 3g'^2}{32\pi^2} \Lambda_g^2 \qquad \longrightarrow \qquad \Lambda_g \sim 9 \, m_h$$

Perturbatively:



If the theory is natural new physics beyond SM must exist at the TEV scale.

Two paradigms:

• Weak Coupling: Supersymmetry



 $\sim~100\,{\rm GeV}$

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• Weak Coupling: Supersymmetry



• Strong Coupling: Technicolor, Composite Higgs, Higgsless, Extra-dimensions ...

HIGGS NGB

Higgs doublet could be a light remnant of strong dynamics.



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Two parameters:

$$m_{
ho}$$
 $g_{
ho}$ $(1 < g_{
ho} < 4\pi)$
Large N : $g_{
ho} \sim \frac{4\pi}{\sqrt{N}}$

Relieves hierarchy problem

$$\delta m_h^2 \sim \frac{3\lambda_t^2}{8\pi^2} m_\rho^2$$

The Higgs scalar itself could be a NGB. If the symmetry is exact it is massless.

Georgi, Kaplan '80s



 $= \frac{G}{H}$ NGB

 $U = e^{i\frac{\pi^{\hat{a}}T^{\hat{a}}}{f}}$

Georgi, Kaplan '80s



 $=\frac{G}{H}$ NGB $U = e^{i\frac{\pi^{\hat{a}}T^{\hat{a}}}{f}}$

Low energy lagrangian

$$\mathcal{L} = f^2 D^{\hat{a}}_{\mu} D^{\hat{a}\mu} + \dots$$

$$\delta \pi = c + \dots$$

$$m_{\rho} = g_{\rho} f$$



Agashe , Contino, Pomarol, '04

$$\frac{SO(5)}{SU(2)_L \otimes SU(2)_R} \longrightarrow GB = (2,2)$$
 Agashe , Contino, Pomarol, '04

Many possibilities:

G	H	N_G	NGBs rep. $[H] = \text{rep.}[SU(2) \times SU(2)]$
SO(5)	SO(4)	4	4 = (2, 2)
SO(6)	SO(5)	5	5 = (1, 1) + (2, 2)
SO(6)	$SO(4) \times SO(2)$	8	$4_{+2} + \bar{4}_{-2} = 2 \times (2, 2)$
SO(7)	SO(6)	6	$6 = 2 \times (1, 1) + (2, 2)$
SO(7)	G_2	7	7 = (1, 3) + (2, 2)
SO(7)	$SO(5) \times SO(2)$	10	$10_0 = (3, 1) + (1, 3) + (2, 2)$
SO(7)	$[SO(3)]^{3}$	12	$(2, 2, 3) = 3 \times (2, 2)$
Sp(6)	$Sp(4) \times SU(2)$	8	$(4, 2) = 2 \times (2, 2), (2, 2) + 2 \times (2, 1)$
SU(5)	$SU(4) \times U(1)$	8	$4_{-5}+\mathbf{ar{4}}_{+5}=2 imes(2,2)$
SU(5)	SO(5)	14	14 = (3,3) + (2,2) + (1,1)

Mrazek et al., 'l l

Deviations from SM:



Deviations from SM:



0

Higgs is an angle,



Higgs cannot be exact NGB

$$h \to h + c$$
 G

G symmetry broken explicitly in SM

$$\lambda_{ij}^{u} \bar{q}_{L}^{i} H^{c} u_{R}^{j} + \lambda_{ij}^{d} \bar{q}_{L}^{i} H d_{R}^{j} + h.c.$$
$$\left|\partial_{\mu} H + i A_{\mu} H\right|^{2}$$

$$SU(2) \times U(1)$$

Higgs cannot be exact NGB

$$h \to h + c$$
 G

G symmetry broken explicitly in SM

Similar to QCD:

$$U(2)_L \times U(2)_R$$

 $U(1)_{em} \times U(1)$

• Bilinear couplings

$$\frac{1}{\Lambda^{d-1}}\bar{q}_L \langle \mathcal{O} \rangle q_R$$

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$$\frac{1}{\Lambda^{d-1}}\bar{q}_L\langle \mathcal{O}\rangle q_R$$

• Linear couplings (partial compositeness)



$$y_{SM} = \epsilon_L \cdot Y \cdot \epsilon_R$$

$$\epsilon = \frac{\Delta}{m_Q}$$

 $\Delta_R \bar{q}_R \mathcal{O}_L + \Delta_L \bar{q}_L \mathcal{O}_R + Y \bar{\mathcal{O}}_L \mathcal{H} \mathcal{O}_R$

• Anarchic scenario

Strong sector couplings have no hierarchies

$$Y^{U,D} \sim g_{\rho} \qquad \qquad y_{SM} = \epsilon_L \cdot Y \cdot \epsilon_R$$

SM hierarchies are generated by the mixings:

- Light quarks elementary
- Top strongly composite

• Anarchic scenario

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SM hierarchies are generated by the mixings:

- Light quarks elementary
- Top strongly composite
- MFV scenario

$$\epsilon_R \propto Id$$
 $\epsilon_L \propto y_{SM}$
MODELS

5D Models



Through AdS/CFT correspondence dual to 4D CFTs. Relevant physics dominated by the lowest modes.

SM gauge fields are obtained from zero modes of bulk fields

 $SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_X$

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 $SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_X$

NGB of G/H obtained from a G gauge theory



Higgs is a Wilson line

$$H = \int_{z_{UV}}^{z_{IR}} A_z dz$$

Each SM chirality is associated to a 5D field of mass c k. SM chiral fermions are obtained by boundary conditions



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Yukawas hierarchies are generated

$$y_{ij}^{SM} = \epsilon_{Li} Y_{ij}^5 \epsilon_{Rj} \qquad \qquad \epsilon \sim \left(\frac{\text{TeV}}{M_p}\right)^{c-\frac{1}{2}}$$

CHM5:



5 = (2, 2) + (1, 1)

 $\widetilde{m}_u \,\overline{(\mathbf{2},\mathbf{2})}_{\mathrm{L}}^{\mathbf{q}_1}(\mathbf{2},\mathbf{2})_{\mathrm{R}}^{\mathrm{u}} + \widetilde{M}_u \,\overline{(\mathbf{1},\mathbf{1})}_{\mathrm{R}}^{\mathbf{q}_1}(\mathbf{1},\mathbf{1})_{\mathrm{L}}^{\mathrm{u}} + \widetilde{m}_d \,\overline{(\mathbf{2},\mathbf{2})}_{\mathrm{L}}^{\mathbf{q}_2}(\mathbf{2},\mathbf{2})_{\mathrm{R}}^{\mathrm{d}} + \widetilde{M}_d \,\overline{(\mathbf{1},\mathbf{1})}_{\mathrm{R}}^{\mathbf{q}_2}(\mathbf{1},\mathbf{1})_{\mathrm{L}}^{\mathrm{d}} + h.c.$

5D models are dual to 4D strongly coupled theories

Arkani-Hamed, Porrati, Randall '00

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5D gauge symmetry \longrightarrow 4D global symmetry $\mathcal{L} = \lambda \bar{q}_L O_R^d$ $\mu \frac{d\lambda}{d\mu} = (d - \frac{5}{2})\lambda$ Contino, Pomarol '04

• d>5/2 irrelevant, small in IR (light generations)

• d<5/2 relevant, large in IR (top)

Hierarchies from dimensional transmutation

• 4D Models

Low energy lagrangian determined by the symmetries. CCWZ procedure

$$U(\Pi) = e^{\frac{i\Pi^{\widehat{a}}T^{\widehat{a}}}{f}} \qquad U(\Pi') = gU(\Pi)h^{\dagger}(\Pi,g) \quad g \in G, \quad h \in H(x)$$
$$U^{\dagger}\partial_{\mu}U = iE^{a}_{\mu}T^{a} + iD^{\widehat{a}}_{\mu}T^{\widehat{a}}$$

• 4D Models

Low energy lagrangian determined by the symmetries. CCWZ procedure

 $U(\Pi) = e^{\frac{i\Pi^{\widehat{a}}T^{\widehat{a}}}{f}} \qquad U(\Pi') = gU(\Pi)h^{\dagger}(\Pi,g) \quad g \in G, \quad h \in H(x)$ $U^{\dagger}\partial_{\mu}U = iE^{a}_{\mu}T^{a} + iD^{\widehat{a}}_{\mu}T^{\widehat{a}}$

An effective lagrangian can be built similar to QCD

$$\mathcal{L} = rac{m_{
ho}^4}{g_{
ho}^2} \left[\mathcal{L}^{(0)}(U, \Phi, \partial/m_{
ho}) + rac{g_{
ho}^2}{(4\pi)^2} \mathcal{L}^{(1)}(U, \Phi, \partial/m_{
ho}) + rac{g_{
ho}^4}{(4\pi)^4} \mathcal{L}^{(2)}(U, \Phi, \partial/m_{
ho}) + \dots
ight]$$

Giudice, Grojean, Pomarol, Rattazzi'07

SM fields are assigned to SO(5) $\Delta^{ij}\bar{q}^i\mathcal{O}^j \qquad \qquad \mathcal{O}\in G$

 $\frac{G}{H}$

$$\frac{G_L \otimes G_R}{G_{L+R}} \qquad \qquad \Omega \to g_L \Omega g_R^{\dagger} \qquad \qquad + \qquad \qquad \frac{G}{H}$$

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and gauge $G_R + G$

$$\mathcal{L}_{2-site} = \frac{f_1^2}{4} \text{Tr} |D_{\mu}\Omega|^2 + \frac{f_2^2}{2} \mathcal{D}_{\mu}^{\widehat{a}} \mathcal{D}^{\mu\widehat{a}} - \frac{1}{4g_{\rho}^2} \rho_{\mu\nu}^A \rho^{A\mu\nu}$$

$$D_{\mu}\Omega = \partial_{\mu}\Omega - iA_{\mu}\Omega + i\Omega\rho_{\mu}$$

$$\frac{G_L \otimes G_R}{G_{L+R}} \qquad \qquad \Omega \to g_L \Omega g_R^{\dagger} \qquad \qquad + \qquad \qquad \frac{G}{H}$$

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$$D_{\mu}\Omega = \partial_{\mu}\Omega - iA_{\mu}\Omega + i\Omega\rho_{\mu}$$

More resonances can be added. Nearest neighbor interaction reproduce extra-dim:



Minimal SO(5)/SO(4) model

De Curtis, Redi, Tesi, 'I I



Composite spin-1 lagrangian:

$\Omega = \frac{SO(5)_L \times SO(5)_R}{SO(5)_R}$	$_{\mathbf{\Phi}}$ $SO(5)$
$SL = -SO(5)_{L+R}$	$\Psi = \frac{1}{SO(4)}$

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Composite spin-1 lagrangian:

$$\Omega = \frac{SO(5)_L \times SO(5)_R}{SO(5)_{L+R}} \qquad \Phi = \frac{SO(5)}{SO(4)}$$

$$\frac{f_1^2}{4} \text{Tr} \left| D_\mu \Omega \right|^2 + \frac{f_2^2}{2} \left(D_\mu \Phi \right)^T \left(D^\mu \Phi \right) - \frac{1}{4g_\rho^2} \rho_{\mu\nu}^a \rho^{a\mu\nu}$$

 $D_{\mu}\Omega = \partial_{\mu}\Omega - iA_{\mu}\Omega + i\Omega\rho_{\mu} \qquad \qquad D_{\mu}\Phi = \partial_{\mu}\Phi - i\rho_{\mu}\Phi$

SO(4) and SO(5)/SO(4) spin-1 resonances.

Spectrum:

$$\begin{split} m_{\rho}^2 &= \frac{g_{\rho}^2 f_1^2}{2} \\ m_{a_1}^2 &= \frac{g_{\rho}^2 (f_1^2 + f_2^2)}{2} \\ m_{\rho_X}^2 &= \frac{g_{\rho_X}^2 f_X^2}{2} \end{split}$$

SM fields are introduced adding kinetic terms for the sources

$$\mathcal{L}_{gauge}^{el} = -\frac{1}{4g_0^2} F^a_{\mu\nu} F^a_{\mu\nu} - \frac{1}{4g_{0Y}^2} Y_{\mu\nu} Y^{\mu\nu}$$

Physical parameters:

$$\begin{array}{rcl} \displaystyle \frac{1}{g^2} & = & \displaystyle \frac{1}{g_0^2} + \displaystyle \frac{1}{g_\rho^2} \\ \\ \displaystyle \frac{1}{g'^2} & = & \displaystyle \frac{1}{g_{0Y}^2} + \displaystyle \frac{1}{g_\rho^2} + \displaystyle \frac{1}{g_{\rho_X}^2} \end{array}$$

$$m_{\rho_{aL}} = \frac{m_{\rho}}{\cos \theta_L}, \quad \tan \theta_L = \frac{g_0}{g_{\rho}}$$

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Each SM fermion couples to Dirac fermion in a rep of SO(5).

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CHM5:



Third generation:

Useful a simple 4D description:

- theoretical:
 - only very few resonances (1?) weakly coupled
 - relevant physics largely independent of 5D or AdS
 - what are the most general models?

- practical:
 - LHC will at best produce the lightest resonances
 - Simplified model useful for LHC

SIGNATURES



$\operatorname{Higgs} \subset \frac{G}{H}$

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Elementary-composite states talk through linear couplings:

Light generations are elementary, top composite.

• Precision Tests

Typical modifications

$$\delta g_{SM} = \kappa \frac{v^2}{m_\rho^2}$$

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} \approx 1 \qquad \qquad \delta \rho_{naive} = \frac{v^2}{f^2}$$
$$\delta \rho_{max} \sim 10^{-3} \qquad \longrightarrow \qquad f > 5 \,\text{TeV}$$

→

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} \approx 1 \qquad \qquad \delta \rho_{naive} = \frac{v^2}{f^2}$$
$$\delta \rho_{max} \sim 10^{-3} \qquad \longrightarrow \qquad f > 5 \,\text{TeV}$$



Composite sector has $SU(2)_L \otimes SU(2)_R \otimes U(1)_X$ symmetry $(Y = T_{3R} + U(1)_X)$

Extended Higgs sectors require extra symmetry

Third generation Z-couplings







Possible problems with ρ at 1-loop

Extend $SU(2)_L \otimes SU(2)_R \otimes U(1)_X$ symmetry

 $P_{LR}:$ $SU(2)_L \times SU(2)_R \to O(4)$

Agashe , Contino, Da Rold, Pomarol, '06

Couplings protected if symmetry respected.

 $T_{3L} = T_{3R}$

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$$\frac{S}{16\pi v^2} \left(H^{\dagger} \tau^a H \right) W^a_{\mu\nu} B^{\mu\nu}$$

Tree-level:



$$S\sim 4\pi v^2\left(\frac{1}{m_\rho^2}+\frac{1}{m_{a_1}^2}\right)$$

$$S < 0.3 \qquad \longrightarrow \qquad m_{\rho} > 2 - 3 \,\mathrm{TeV}$$

General Higgs lagrangian:

$$\mathcal{L} = \frac{1}{2} (\partial_{\mu} h)^{2} + \frac{v^{2}}{4} \operatorname{Tr} \left(D_{\mu} \Sigma^{\dagger} D^{\mu} \Sigma \right) \left[1 + 2\kappa_{V} \frac{h}{v} + \kappa_{hh} \frac{h^{2}}{v^{2}} \dots \right]$$
$$- m_{i} \bar{\psi}_{Li} \Sigma \left(1 + \kappa_{F} \frac{h}{v} + \dots \right) \psi_{Ri} + h.c. + \dots$$



 $SM: \quad \kappa_F = \kappa_V = 1$

Corrections determined by group theory:

$$m_W^2 = \frac{g^2 f^2}{4} \sin^2 \frac{h}{f} \qquad \longrightarrow \qquad \kappa_V = \sqrt{1-\xi} \qquad \qquad \xi = \frac{v^2}{f^2}$$



CHM5:

$$m_t \propto \sin \frac{h}{f} \cos \frac{h}{f} \qquad \longrightarrow \qquad \kappa_F = \frac{1 - 2\xi}{\sqrt{1 - \xi}}$$

CHM4:







Goldstone symmetry protects the couplings also at loop-level



Gluon and photons couplings often determined by $\kappa_V - \kappa_F$

Precision tests:

$$\frac{v^2}{f^2} < 0.1$$

Deviation very difficult to see at LHC.

WW scattering not exactly unitarized





$$A(W^+W^- \to W^+W^-) \simeq \frac{s}{v^2}(1-\kappa_V^2)$$

$$A(W^+W^- \to hh) \simeq \frac{s}{v^2}(\kappa_{hh} - \kappa_V^2)$$

 $\Lambda < \frac{3\,{\rm TeV}}{\sqrt{1-k_V^2}}$

Most likely not visible at LHC

Contino et al. '09


• Double Higgs production:

Grober, Muhlletner '10 Contino et al. '12 • Flavor

Resonance exchange generates 4-Fermi operators

 $\sim \frac{g_{
ho}^2}{m_{
ho}^2}$

 $\Delta F = 2$ transitions generated by mixing

$$q \xrightarrow{\epsilon_L} \rho \xrightarrow{\epsilon_R} q \\ \epsilon_L \xrightarrow{\epsilon_R} q \\ \epsilon_R \xrightarrow{\epsilon_R} q \\ \epsilon_R \xrightarrow{\epsilon_R} q \\ \epsilon_R \xrightarrow{\epsilon_R} \xrightarrow{\epsilon_R} \epsilon_R \xrightarrow{\epsilon_R} \xrightarrow{\epsilon_R} \epsilon_R \xrightarrow{\epsilon_R} \{\epsilon_R} \xrightarrow{\epsilon_R} \epsilon_R \xrightarrow{\epsilon_R} \{\epsilon_R} \xrightarrow{\epsilon_R} \epsilon_R \xrightarrow{\epsilon_R} \{\epsilon_R} \xrightarrow{\epsilon_R} \xrightarrow{\epsilon_R} \{\epsilon_R} \xrightarrow{\epsilon_R} \{\epsilon_R} \xrightarrow{\epsilon_R} \xrightarrow{\epsilon_R} \{\epsilon_R} \xrightarrow{\epsilon_R} \xrightarrow{$$

FCNC of the light generation are suppressed by the mixings.

Flavor superior to TC theories though not perfect.

$$C_4^K \sim \frac{g_\rho^2}{m_\rho^2} \frac{m_d \, m_s}{v^2}$$

 $m_{\rho} > 20 \text{ TeV}$

Csaki, Falkowski, Weiler, '08



 $C_4^K \bar{d}_R^{\alpha} s_L^{\alpha} \bar{d}_L^{\beta} s_R^{\beta}$



$b \to s \gamma$

Neutron EDM

 $m_{\rho} > 2 g_{\rho} \,\mathrm{TeV}$

 $\mu \to e \gamma$

 $m_{\rho} > 30 g_{\rho} \,\mathrm{TeV}$



 $\mu \to e\gamma$

 $m_{\rho} > 30 g_{\rho} \,\mathrm{TeV}$

CP violation in D-system:

$$a_{D^0 \to K^+ K^-} - a_{D^0 \to \pi^+ \pi^-} = (-0.67 \pm 0.16)\%$$
 LHCb '12

Reasonable in composite Higgs

$$m_{\rho} \simeq \frac{g_{\rho}}{4\pi} \times 10 \,\mathrm{TeV}$$

Keren-Zur et al., '12

• Direct Searches

Heavy resonances mostly coupled to 3rd generation + Higgs

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Heavy resonances mostly coupled to 3rd generation + Higgs

Spin-I: gluon, electro-weak



Decay into 3rd generation or heavy fermions.



ATLAS-CONF-2013-052

CMS-PAS-B2G-12-005



Gluon resonances excluded up to 2 TeV!

Spin-1/2 : Top partners could be lighter + exotic charges

$$\left(\begin{array}{c}T\\B\end{array}\right) + \left(\begin{array}{c}T_{\frac{5}{3}}\\T_{\frac{2}{3}}\end{array}\right) \qquad \qquad \tilde{T}$$

Spin-1/2 : Top partners could be lighter + exotic charges

$$\left(\begin{array}{c}T\\B\end{array}\right) + \left(\begin{array}{c}T_{\frac{5}{3}}\\T_{\frac{2}{3}}\end{array}\right) \qquad \qquad \tilde{T}$$

• Double production:



Contino, Servant. '08

• Single production:



Mrazek, Wulzer '09 Aguilar-Saveedra '09 De Simone et al. '12



ATLAS-CONF-2013-060



CMS-PAS B2G-12-012



HIGGS MASS

SM couplings break NGB symmetry

$$\epsilon_{t_L}$$
 ϵ_{t_R} g

Higgs potential generated at 1-loop:

$$V(h) \sim \frac{N_c}{16\pi^2} \epsilon_{L,R}^2 m_{\rho}^4 \hat{V}\left(\frac{h}{f}\right) + \dots$$

SM couplings break NGB symmetry

$$\epsilon_{t_L}$$
 ϵ_{t_R} g

Higgs potential generated at 1-loop:

$$V(h) \sim \frac{N_c}{16\pi^2} \epsilon_{L,R}^2 m_{\rho}^4 \hat{V}\left(\frac{h}{f}\right) + \dots$$

$$V(h) \approx a \sin^2 \frac{h}{f} + b \sin^2 \frac{h}{f} \cos^2 \frac{h}{f}$$

$$v \ll f \longrightarrow a \approx -b$$

Recall pions:

$$\mathcal{L} = f_{\pi}^{2} |D_{\mu}U|^{2} + a \Lambda_{QCD}^{2} \operatorname{Tr}[m \cdot (U + U^{\dagger})]$$
$$D_{\mu}U = \partial_{\mu}U + ieA_{\mu}U$$
$$m_{\pi^{+}}^{2} = m_{\pi^{0}}^{2} = a' \Lambda_{QCD}(m_{u} + m_{d})$$

Recall pions:

I-loop:

$$\mathcal{L} = f_{\pi}^{2} |D_{\mu}U|^{2} + a \Lambda_{QCD}^{2} \operatorname{Tr}[m \cdot (U + U^{\dagger})]$$

$$D_{\mu}U = \partial_{\mu}U + ieA_{\mu}U$$

$$m_{\pi^{+}}^{2} = m_{\pi^{0}}^{2} = a' \Lambda_{QCD}(m_{u} + m_{d})$$

$$\pi^{+} \qquad \pi^{+} \qquad \pi^{+} \qquad \pi^{+}$$

$$\delta m_{\pi^{+}}^{2} = \frac{3e^{2}}{32\pi^{2}} \int dp^{2} \sim \frac{3\alpha_{EM}}{8\pi} \Lambda^{2}$$

Vectors effective action:

$$\mathcal{L}_{\text{eff}} = \frac{1}{2} P_{\mu\nu}^{T} \Big[\widehat{\Pi}_{0}^{X}(p^{2}) X^{\mu} X^{\nu} + \widehat{\Pi}_{0}(p^{2}) \operatorname{Tr} \big[A^{\mu} A^{\nu} \big] + \widehat{\Pi}_{1}(p^{2}) \Phi A^{\mu} A^{\nu} \Phi^{T} \Big]$$

 $\widehat{\Pi}_0(p^2) = \Pi_a(p^2), \quad \widehat{\Pi}_0^X(p^2) = \Pi_X(p^2), \quad \widehat{\Pi}_1(p^2) = 2\left[\Pi_{\widehat{a}}(p^2) - \Pi_a(p^2)\right]$

$$\mathcal{L}_{\text{eff}}^{gauge} = \frac{1}{2} P_{\mu\nu}^{T} \left[\left(\Pi_{0}(p^{2}) + \frac{s_{h}^{2}}{4} \Pi_{1}(p^{2}) \right) A_{aL}^{\mu} A_{aL}^{\nu} \right. \\ \left. + \left(\Pi_{Y}(p^{2}) + \frac{s_{h}^{2}}{4} \Pi_{1}(p^{2}) \right) Y^{\mu} Y^{\nu} + 2s_{h}^{2} \Pi_{1}(p^{2}) \, \widehat{H}^{\dagger} T_{L}^{a} Y \widehat{H} \, A_{\mu}^{aL} Y_{\nu} \right]$$

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Coleman-Weinberg effective potential

$$V(h)_{gauge} = \frac{9}{2} \int \frac{d^4p}{(2\pi)^4} \ln\left[1 + \frac{1}{4} \frac{\Pi_1(p^2)}{\Pi_0(p^2)} \sin^2 \frac{h}{f}\right] \quad \approx \int \frac{d^4p}{(2\pi)^4} \frac{9\Pi_1}{8\Pi_0} \sin^2 \frac{h}{f}$$

Fermions:

$$V(h)_{fermions} = -2N_c \int \frac{d^4p}{(2\pi)^4} \left[\ln \Pi_{b_L} + \ln \left(p^2 \Pi_{t_L} \Pi_{t_R} - \Pi_{t_L t_R}^2 \right) \right]$$

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CHM5:

$$\begin{split} \mathcal{L}_{\text{eff}} = & \bar{q}_L \not p \left[\Pi_0^q(p^2) + \frac{s_h^2}{2} \left(\Pi_1^{q_1}(p^2) \, \widehat{H}^c \widehat{H}^{c\dagger} + \Pi_1^{q_2}(p^2) \, \widehat{H} \widehat{H}^{\dagger} \right) \right] q_L \\ & + \bar{u}_R \not p \left(\Pi_0^u(p^2) + \frac{s_h^2}{2} \, \Pi_1^u(p^2) \right) u_R + \bar{d}_R \not p \left(\Pi_0^d(p^2) + \frac{s_h^2}{2} \, \Pi_1^d(p^2) \right) d_R \\ & + \frac{s_h c_h}{\sqrt{2}} M_1^u(p^2) \, \bar{q}_L \widehat{H}^c u_R + \frac{s_h c_h}{\sqrt{2}} M_1^d(p^2) \, \bar{q}_L \widehat{H} d_R + h.c. \,. \end{split}$$

$$V(h)_{fermions} \approx -N_c \int \frac{d^4 p}{(2\pi)^4} \left[\frac{\Pi_1^{q_1}}{\Pi_0^q} + \frac{\Pi_1^u}{\Pi_0^u} \right] \sin^2 \frac{h}{f} + N_c \int \frac{d^4 p}{(2\pi)^4} \left[\frac{(M_1^u)^2}{p^2 \Pi_0^q \Pi_0^u} \right] \sin^2 \frac{h}{f} \cos^2 \frac{h}{f}$$

Simplified models:

$$\Pi_{gauge}[m_V] = \frac{p^2}{p^2 - m_V^2}$$
$$\widehat{\Pi}[m_1, m_2, m_3] = \frac{\left(m_2^2 + m_3^2 - p^2\right)}{p^4 - p^2(m_1^2 + m_2^2 + m_3^2) + m_1^2 m_2^2}$$

$$\widehat{M}[m_1, m_2, m_3] = -\frac{m_1 m_2 m_3}{p^4 - p^2 (m_1^2 + m_2^2 + m_3^2) + m_1^2 m_2^2}$$

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Gauge potential:

$$V(h)_{gauge} \approx \int \frac{d^4p}{(2\pi)^4} \frac{9}{8} \frac{\Pi_1}{\Pi_0} \sin^2 \frac{h}{f}$$
$$= \frac{9}{4} \frac{1}{16\pi^2} \frac{g_0^2}{g_\rho^2} \frac{m_\rho^4 \left(m_{a_1}^2 - m_\rho^2\right)}{m_{a_1}^2 - m_\rho^2 (1 + g_0^2/g_\rho^2)} \ln\left[\frac{m_{a_1}^2}{m_\rho^2 (1 + g_0^2/g_\rho^2)}\right] \sin^2 \frac{h}{f}$$

Potential is finite with a single G multiplet!

ESTIMATES



$$\mathcal{L}_{Yuk} = y_t f \, \frac{s_h c_h}{h} (\bar{q}_L H^c t_R + h.c.) \qquad \longrightarrow \qquad V(h)_{Yuk} \sim N_c \frac{y_t^2}{16\pi^2} m_f^2 f^2 s_h^2 c_h^2$$

$$\mathcal{L}_{kin} = \epsilon_L^2 \, s_h^2 \, \bar{t}_L \, /\!\!D t_L + 2 \, \epsilon_R^2 \, s_h^2 \, \bar{t}_R \, /\!\!D t_R \qquad \longrightarrow \qquad V(h)_{kin} \sim N_c \frac{2\epsilon_R^2 - \epsilon_L^2}{32\pi^2} \, m_f^4 \, s_h^2$$

ESTIMATES



$$\mathcal{L}_{Yuk} = y_t f \, \frac{s_h c_h}{h} (\bar{q}_L H^c t_R + h.c.) \qquad \longrightarrow \qquad V(h)_{Yuk} \sim N_c \frac{y_t^2}{16\pi^2} m_f^2 f^2 s_h^2 c_h^2$$

$$\mathcal{L}_{kin} = \epsilon_L^2 \, s_h^2 \, \bar{t}_L \, /\!\!D t_L + 2 \, \epsilon_R^2 \, s_h^2 \, \bar{t}_R \, /\!\!D t_R \qquad \longrightarrow \qquad V(h)_{kin} \sim N_c \frac{2\epsilon_R^2 - \epsilon_L^2}{32\pi^2} \, m_f^4 \, s_h^2$$

Potential:

$$V(h) \approx \alpha s_h^2 - \beta s_h^2 c_h^2$$
 $s_h \equiv \sin \frac{h}{f} = \frac{v}{f}$

Quartic is determined by top Yukawa,

$$m_h \sim \sqrt{\frac{N_c}{2}} \frac{y_t}{\pi} \frac{m_f}{f} v$$

•CHM5

General scan:



MR, Tesi '12

 $f = 500 \,\mathrm{GeV}$

•CHM5

General scan:

MR, Tesi '12





For mH=125 GeV, fermionic partners often rule out!

Thursday, October 31, 2013



New fermions should be seen in the near future!

Thursday, October 31, 2013



Panico, MR, Tesi, Wulzer '12

$$\Delta = \operatorname{Max}_{i} \left| \frac{\partial \log m_{Z}}{\partial \log x_{i}} \right|$$









Natural region of the theory will be tested at LHC!

+ The Higgs as Nambu-Goldstone boson is a compelling possibility for stabilizing the electro-weak scale.

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- + Realistic scenarios can be build
- Unclear UV completion

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± Many smart mechanisms have been proposed
+ Models are predictive.

New resonances must be present nearby with a specific pattern. New effects expected in flavor and Higgs physics.

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- No deviations from the SM have been seen where they could be expected.

++ LHC will tell if the electro-weak scale is natural. Very exciting experimentally.



Gripaios, Pomarol, Riva, Serra '09 Redi, Tesi '12

5 GBs:

$$5 = (2, 2) + 1$$

Fermions can be coupled to the $6=(2,2)+2 \times 1$

$$q_L \to \frac{1}{\sqrt{2}} \begin{pmatrix} b_L \\ -ib_L \\ t_L \\ it_L \\ 0 \\ 0 \end{pmatrix} \qquad \qquad t_R \to \begin{pmatrix} 0 \\ 0 \\ 0 \\ i\cos\theta t_R \\ \sin\theta t_R \end{pmatrix}$$

For
$$\theta = \frac{\pi}{4}$$
 singlet becomes exact GB.

$$f = 800 \,\mathrm{GeV}$$



$$f = 800 \,\mathrm{GeV}$$



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ESTIMATES

$$\mathcal{L} = \left(1 + \epsilon_L^2 \sum_i I_L^{(i)}(s_h)\right) \bar{q}_L \partial q_L + \left(1 + \epsilon_R^2 \sum_i I_R^{(i)}(s_h)\right) \bar{t}_R \partial t_R + y_t f M(s_h) \bar{t}_L t_R + h.c. ,$$

Loops of SM fields generate:

$$V_{\text{leading}} \sim \frac{N_c}{16\pi^2} m_{\psi}^4 \sum_i \left[\epsilon_L^2 I_L^{(i)}(s_h) + \epsilon_R^2 I_R^{(i)}(s_h) \right]$$

$$V_{\text{sub-leading}} \sim \frac{N_c}{16\pi^2} m_{\psi}^2 f^2 \left[y_t^2 M^2(s_h) + \dots \right] \qquad \left(y_t \sim \epsilon_L \epsilon_R \frac{m_{\psi}}{f} \right)$$

$$s_h \equiv \sin\frac{h}{f} = \frac{v}{f}$$

Two different trigonometric structures needed to tune.

• Tuning at leading order

$$m_h^2 \sim \frac{N_c}{2\pi^2} y_t \frac{m_\psi^3}{f^3} v^2 \qquad \qquad \longrightarrow \qquad \Delta = \frac{\delta m_h^2}{m_h^2} \sim \frac{f^2}{v^2}$$

• Tuning with sub-leading terms (CHM5, CHM10...)

$$m_h^2 \sim \frac{N_c}{2\pi^2} y_t^2 \frac{m_\psi^2}{f^2} v^2 \qquad \longrightarrow \qquad \Delta = \frac{\delta m_h^2}{m_h^2} \sim \frac{m_\psi}{y_t f} \times \frac{f^2}{v^2}$$

• Composite tR (CHMI4)

$$m_h^2 \sim \frac{N_c}{2\pi^2} y_t^2 \frac{m_\psi^2}{f^2} v^2 \qquad \longrightarrow \qquad \Delta = \frac{\delta m_h^2}{m_h^2} \sim \frac{f^2}{v^2}$$