# Bridging Composite Higgs and Technicolor with Higgs data

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# Introduction

We discuss the possibility that the observed Higgs (126 GeV) at the LHC is a mixed state of composite Higgs and technicolor Higgs.

- Techinicolor Higgs

  Higgs boson is a fermion condensation from a strong dynamics.

  Susskind, 1978; Weinberg, 1978

- Composite Higgs

  Higgs boson is a pseudo Goldstone Boson from a global symmetry.

  Georgi, Kaplan, 1984

The two scenarios are possible to be unified in one framework. We are going to explore the scalar phenomenology in this scenario.

# Fundamental Theory

The underlying dynamics is a $SU(2)_{TC}$ gauge theory with 2 Dirac techni-quarks. The Lagrangian can be written as:

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \bar{Q}_j (i\sigma^\mu D_\mu) Q_j - M^{ij} Q_i Q_j + h.c.$$
$$Q^T = \begin{pmatrix} U_L & D_L & \tilde{U}_L & \tilde{D}_L \end{pmatrix}$$
$$\tilde{U}_L = -i\sigma^2 U_R^*, \quad \tilde{D}_L = -i\sigma^2 D_R^*$$

We have 4 Weyl fermions $\Rightarrow$ the global symmetry is $SU(4)$. In the massless limit the condensation,

$$\langle Q^i Q^j \rangle = \mathbf{6}_{SU(4)} \to \mathbf{5}_{Sp(4)} \oplus \mathbf{1}_{Sp(4)}$$

transforms as a 2-index anti-symmetric tensor and breaks the global symmetry$SU(4) \to Sp(4)$. The coset contains 5 Goldstone bosons, transforming as a **5** of $Sp(4)$.

# The Vaccum

In terms of $\Sigma_{ij} \sim Q_i Q_j$, the EW preserving vacuum is,

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

with 10 unbroken generators $S^i$,and 5 broken generators $X^a$. We will identify $S^{1,2,3}$ to be $SU(2)_L$ and $S^{3,4,5}$ to be $SU(2)_R$, .

The most general vacuum is obtained by applying a transformation,

$$\Sigma_0 = e^{i\gamma} \begin{pmatrix} \cos\theta \; i\sigma_2 & \sin\theta \; 1_{2\times 2} \\ -\sin\theta \; 1_{2\times 2} & -\cos\theta \; i\sigma_2 \end{pmatrix}$$

with $\theta$ associated with EW breaking. In unitary gauge, the sigma field is,

$$\begin{aligned} \Sigma &= e^{iY^4 h/f + iY^5 \eta/f} \cdot \Sigma_0 \\ Y^4 &= X^4 , \quad Y^5 = c_\theta X^5 - s_\theta S^8 \end{aligned}$$

where $h, \eta$ are pNGBs and $Y^4, Y^5$ are broken generators in the general vacuum.

# Sigma Lagrangian

The chiral lagrangian is therefore given by:

$$\mathcal{L}_{\rm CCWZ} = \kappa_G(\sigma) f^2 \mathrm{Tr}[(D_\mu\Sigma)^\dagger D^\mu \Sigma] + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}M^2\kappa_M(\sigma)\sigma^2 +$$
$$f\left(\kappa_t(\sigma)\, {y'}^{ij}_u (Q_i u^c_j)^\dagger_\alpha + \kappa_b(\sigma)\, {y'}^{ij}_d (Q_i d^c_j)_\alpha + \kappa_l(\sigma)\, {y'}^{ij}_l (L_i l^c_j)^\dagger_\alpha\right) \mathrm{Tr}[P^\alpha\Sigma] + h.c.$$

where we introduce the kinematic term to $\sigma$ particle and yukawa terms to SM fermions. The mass spectrum is:

$$m_W^2 = 2g^2 f^2 \sin^2\theta = \tfrac{g^2 v^2}{4}\,, \quad m_Z^2 = \tfrac{m_W^2}{\cos^2\theta_W}\,, \quad m_f = {y'}_f f \sin\theta = \tfrac{y'_f v}{2\sqrt{2}}$$

$$m_h^2 = m_\eta^2 \sin^2\theta \quad (\text{before mixing with } \sigma)$$

# $h$ and $\eta$ Couplings

Expanding the chiral Lagrangian in terms of $1/f$, one obtains the pNGB couplings with SM gauge bosons and fermions,

- For the $h$ field:

$$\begin{aligned} g_{hWW} &= g^{SM}_{hWW} c_\theta\,, \quad g_{hhWW} = g^{SM}_{hhWW} c_{2\theta} \\ g_{hZZ} &= g^{SM}_{hZZ} c_\theta\,, \quad g_{hhZZ} = g^{SM}_{hhZZ} c_{2\theta} \\ g_{hf\bar{f}} &= g^{\mathrm{SM}}_{hf\bar{f}} c_\theta\,, \quad g_{hhf\bar{f}} = -\frac{m_f}{v^2} s^2_\theta \end{aligned}$$

- For the $\eta$ field:

$$g_{\eta\eta WW} = -g^{SM}_{hhWW} s^2_\theta\,, \quad g_{\eta\eta ZZ} = -g^{SM}_{hhZZ} s^2_\theta$$

$$g_{\eta^2 f\bar{f}} = -\tfrac{m_f}{v^2} s^2_\theta$$

Lagrangian is invariant for $\eta \to -\eta \;\Rightarrow\;$ no linear $\eta$ coupling

only true at the tree level

# $\sigma$ Couplings

- For the $\sigma$ field, through expanding the functions $\kappa_{M,G,t}$ as,

$$\kappa_{M,G,t}(\sigma) = 1 + \kappa^{(1)}_{M,G,t}\frac{\sigma}{4\pi f} + \frac{1}{2}\kappa^{(2)}_{M,G,t}\frac{\sigma^2}{(4\pi f)^2} + \cdots$$

and defining coefficients,

$$\tilde{\kappa}_G = \frac{\kappa_G^{(1)}}{2\sqrt{2}\pi}\,, \quad \tilde{\kappa}_f = \frac{\kappa_f^{(1)}}{\sqrt{2}\pi}\,, \quad \tilde{\kappa}_G^{(2)} = \frac{\kappa_G^{(2)}}{4\pi^2}\,, \qquad \tilde{\kappa}_f^{(2)} = \frac{\kappa_f^{(2)}}{2\pi^2}$$

one find the couplings,

$$\begin{aligned} g_{\sigma WW} &= g^{\mathrm{SM}}_{hWW}\tilde{\kappa}_G s_\theta\,, \quad g_{\sigma^2 WW} = g^{\mathrm{SM}}_{h^2 WW}\tilde{\kappa}_G^{(2)} s_\theta^2 \\ g_{\sigma f\bar{f}} &= g^{\mathrm{SM}}_{hf\bar{f}}\tilde{\kappa}_f s_\theta\,, \quad g_{\sigma^2 f\bar{f}} = \tilde{\kappa}_f^{(2)}\frac{m_f}{v^2}s_\theta^2 \end{aligned}$$

In technicolor limit i.e. $\theta = \pi/2$, we have the results $\tilde{\kappa}_G = \tilde{\kappa}_f = 1$.

# Physical Higgs

Since $\kappa_{M,G,t}$ introduce mixing between between $h$ and $\sigma$, we can write:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h \\ \sigma \end{pmatrix}$$

The scalar couplings have therefore the forms:

$$\begin{aligned} g_{h_1} &= c_\alpha g_h + s_\alpha g_\sigma \\ g_{h_2} &= -s_\alpha g_h + c_\alpha g_\sigma \end{aligned}$$

and we will impose $m_{h_1} = m_{Higgs} \sim 126$ GeV.

For the single $h$ or $\eta$ production, there are four free parameters:

$$\theta\,, \quad \alpha\,, \quad \tilde{\kappa}_G\,, \quad \tilde{\kappa}_t$$

# Fine Tuning

We can compute the Higgs potential as a function $\theta$:

$$\begin{aligned} V_{\rm scalars} &= \kappa_G(\sigma)\, V_{\rm gauge} + \kappa_t^2(\sigma)\, V_{\rm top} + \kappa_m(\sigma)\, V_m \\ &\simeq y_t'^2 C_t \cos^2\theta - 4C_m \cos\theta + \cdots \end{aligned}$$

where $C_{t,m}$ are order-1 coefficient determined by the dynamics. The minimum of the potential is given by,

$$\cos\theta_{\rm min} = \frac{2C_m}{y_t'^2 C_t}\,, \qquad \text{for } y_t'^2 C_t > 2|C_m|\,.$$

Note that a small techni-fermion mass would push the vacuum towards the Technicolour limit $\theta = \pi/2$. Fine tuning is required for $2C_m \to y_t'^2 C_t$, if we demand a composite Higgs limit $\theta \to 0$.

# EWPTs

EWPT bounds are more constraint in composite Higgs type of models. The $S$ and $T$ parameters in this model read:

$$\begin{aligned}\Delta S &= \frac{1}{6\pi}\left[(1-k_{h_1}^2)\ln\frac{\Lambda}{m_{h_1}} - k_{h_2}^2\ln\frac{\Lambda}{m_{h_2}} + N_D\sin^2\theta\right]\,;\\ \Delta T &= -\frac{3}{8\pi\cos^2\theta_W}\left[(1-k_{h_1}^2)\ln\frac{\Lambda}{m_{h_1}} - k_{h_2}^2\ln\frac{\Lambda}{m_{h_2}}\right]\,;\end{aligned}$$

where $k_{h_1}$ and $k_{h_2}$ signal the deviation from SM higgs,

$$\begin{aligned}k_{h_1} &= \cos(\theta-\alpha) + (\tilde{\kappa}_G - 1)\sin\theta\sin\alpha\,,\\ k_{h_2} &= \sin(\theta-\alpha) + (\tilde{\kappa}_G - 1)\sin\theta\cos\alpha\end{aligned}$$

The logarithmic term is from the modification of Higgs couplings and the term proportional to $\sin^2\theta$ origins from the loops of techni-fermions and we set the cut off scale to be $\Lambda = 4\pi f$.

# Global Fit

Through a $\chi^2$ analysis, we can use the Higgs measurements to extract bound for the parameters. This approach is illustrated in the following:

- The signal strength for Higgs decays is defined as:

$$\mu_i = \frac{\sum_m \sigma_m}{\sum_m \sigma_{m,SM}} \times \frac{Br_i}{Br_{i,SM}}$$

- Cross section and partial decay width in $\mu_i$ can be rescaled:

$$\frac{\sigma_{ggh}}{\sigma_{ggh,SM}} = k_g^2 , \quad \frac{\sigma_{Wh}}{\sigma_{Wh,SM}} = k_W^2 , \quad \frac{\sigma_{Zh}}{\sigma_{Zh,SM}} = k_Z^2 , \quad \frac{\sigma_{tth}}{\sigma_{tth,SM}} = k_t^2$$

$$\frac{\Gamma_{WW}}{\Gamma_{WW,SM}} = k_W^2 , \quad \frac{\Gamma_{ZZ}}{\Gamma_{ZZ,SM}} = k_Z^2 , \quad \frac{\Gamma_{bb}}{\Gamma_{bb,SM}} = k_b^2 , \quad \cdots\cdots$$

  where those $k_i$s factors are functions of $\theta$, $\alpha$, $\tilde{\kappa}_G$ and $\tilde{\kappa}_t$.

- The $\chi^2$ function is employed to fit experimental data:

$$\chi^2 = \sum_i \frac{(\mu_i - \mu_{i,exp})^2}{\sigma_i^2}$$

# PNGB Higgs Limit

In this case, Higgs is purely pNGB $h$. For $\alpha = 0$, $\tilde{\kappa}_G = 0$,Higgs couplings and $S$, $T$ are functions of $\theta$, an upper bound can be extracted. The limits at $3\sigma$ are summarised in the table:

| | $H$ couplings | $\mathrm{EWPT}_{\mathrm{SU(2)_{TC}}}$ | $\mathrm{EWPT}_{\mathrm{Sp(4)_{TC}}}$ | $\mathrm{EWPT}_{\mathrm{Sp(6)_{TC}}}$ |
|---|---|---|---|---|
| $\theta <$ | 0.67 | 0.239 | 0.227 | 0.216 |

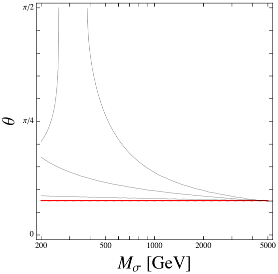


Figure : Upper bound on $\theta$ as a function of the mass of $\sigma$. The red curve correspond to the decoupling limit $\theta < 0.239$, while for the other lines correspond to $\tilde{\kappa}_G = 0.5$, 1 and 1.2, while we keep $\alpha = 0$ and $N_D = 2$.

## Technicolor Limit

In this case, the Higgs is associated with the techni-$\sigma$, i.e. $\theta = \alpha = \pi/2$.

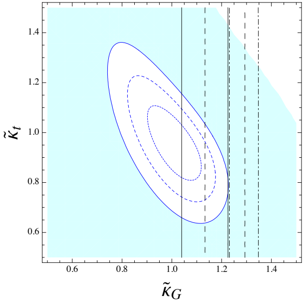


Figure : Region allowed by the Higgs couplings in the Technicolour limit with 1, 2 and 3 $\sigma$ contours. The regions within the vertical lines are allowed by EWPTs at $3\sigma$ for $\mathrm{SU(2)_{TC}}$ (solid), $\mathrm{Sp(4)_{TC}}$ (dashed) and $\mathrm{Sp(6)_{TC}}$ (dash-dotted).

# General Case

Consider a special scenario, $\tilde{\kappa}_G = \tilde{\kappa}_t = 1$, the $g_{h1}$ and $g_{h2}$ depend on $\theta - \alpha$. In such a case, EWPT prefers a small $\theta$ and excludes the technicolor corner.

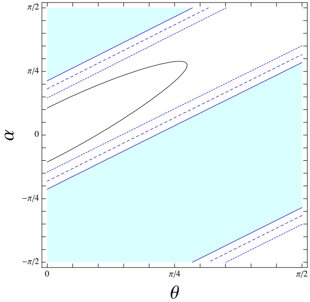


Figure : Region allowed by the Higgs couplings for $\tilde{\kappa}_G = \tilde{\kappa}_t = 1$ and $m_{h_2} = 1$ TeV. The black line indicates the $3\sigma$ bound from EWPTs.

# $\eta$-$f$-$f$ Coupling

Linear $\eta$-$f$-$f$ coupling is dynamically generated by combining the gauge interaction with the top Yukawa:

$$\begin{aligned} \mathcal{O}_2 &= \frac{\tilde{\mu}}{2\pi^2} (Qt^c)^\dagger_\alpha (i\sigma_2)\, tr\left(g^2 T^i_L \Sigma T^{i*}_L \Sigma^\dagger P^\alpha\right) \\ &+ \frac{\tilde{\mu}}{2\pi^2} (Qt^c)^\dagger_\alpha (i\sigma_2)\, tr\left(g'^2 T^3_R \Sigma T^{3*}_R \Sigma^\dagger P^\alpha\right) \end{aligned}$$

Assuming the operator $\mathcal{O}_2$ will give a 1-loop correction to the fermion mass, it is reasonable to demand that $\tilde{\mu} = m_f / \sin\theta$, the coupling $\eta$-$f$-$f$ is:

$$g_{\eta f\bar{f}} = \frac{(3g_2^2 - g_1^2)}{16\pi^2} \frac{m_f}{v} \sin\theta$$

with $m_f$ the mass of the fermion. For top quark, the coupling is not negligible.

# $\eta$-$V$-$V$ Coupling

Only the anomaly term can make $\eta$ decay into double gauge bosons. The triangle diagram gives the amplitude:

$$\mathcal{M} = \frac{g_{\eta V_1 V_2}}{8\pi^2\sqrt{2}f}\epsilon_{\mu\nu\rho\sigma}\epsilon_1^{\mu}(p_1)\epsilon_2^{\nu}(p_2)p_1^{\rho}p_2^{\sigma}$$

with the different couplings :

$$g_{\eta WW} = \frac{g^2 s_\theta c_\theta}{16\sqrt{2}\pi^2 v} \qquad g_{\eta ZZ} = \frac{(g^2 - g'^2)s_\theta c_\theta}{16\sqrt{2}\pi^2 v} \qquad g_{\eta Z\gamma} = \frac{g g' s_\theta c_\theta}{16\sqrt{2}\pi^2 v}$$

$$g_{\eta\gamma\gamma} = 0 \qquad g_{\eta gg} = 0$$

No $\eta$ coupling to diphoton and gluons due to the fact that $Y^5$ is traceless.

# Partial width

We find the following partial widths:

$$\Gamma(\eta \to V_1 V_2) = \frac{g^2_{\eta V_1 V_2}}{32\pi m^3_\eta} \left[ \left\{ m^2_\eta - (m_{V_1} + m_{V_2})^2 \right\} \left\{ m^2_\eta - (m_{V_1} - m_{V_2})^2 \right\} \right]^{3/2} \frac{1}{1+\delta_{V_1 V_2}}$$

$$\begin{aligned}
\Gamma(\eta \to gg) &= \frac{\alpha \alpha_s^2 m_\eta^3}{8\pi^2 m_W^2 \sin^2\theta_W} \frac{g^2_{\eta tt} v^2}{m_t^2} F_1^2(x_t) \\
\Gamma(\eta \to \gamma\gamma) &= 1/2\ N_c^2 \frac{\alpha^2}{\alpha_s^2} \left(\frac{2}{3}\right)^4 \Gamma(\eta \to gg) \\
\Gamma(\eta \to f\bar{f}) &= \frac{N_c g^2_{\eta f \bar{f}}}{8\pi} m_\eta \sqrt{1 - \frac{4 m_f^2}{m_\eta^2}}
\end{aligned}$$

where $F_1(x_t)$ is the loop factor from top quark,

$$F_1(x_t) = 1/2\ x \left(1 + (1 - x_t) \sin^2\left(x_t^{-1/2}\right)\right)$$

# Branching ratios

In the mass region of 200 GeV $< m_\eta <$ 350 GeV, the decay width is dominated by the $W^+W^-$, $Z\gamma$, $ZZ$ and $b\bar{b}$, and for $m_\eta >$ 350 GeV, $t\bar{t}$ becomes the dominating final states.

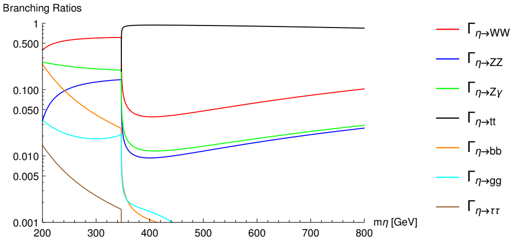


Figure : Branching ratios for the $\eta$ particle as a function of $m_\eta$.

# $\eta$ production

At a Run II LHC, with $m_\eta = 250$ GeV, the cross section for the leading channel $pp \to \eta\eta jj$ is around 0.43 fb.

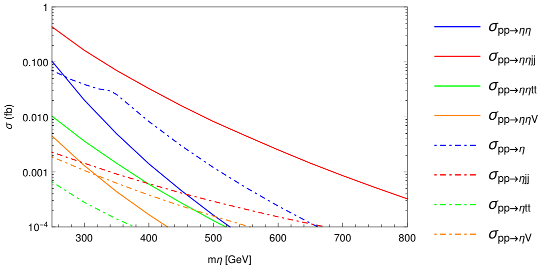


Figure : Production rate as the function of $m_\eta$ at the LHC with $\sqrt{s} = 13$ TeV. We set the PDF to be MSTW2008NLO. The renormalization and factorization scales are fixed to be $\mu_R = \mu_F = \Sigma_f m_f/2$.

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- In our model, the $\eta \to VV'$ is realized via the anomaly term, and $\eta \to \bar{f}f$ is dynamically generated. The dominant production at LHC Run II will be the pair VBF process, i.e. $gg \to \eta\eta jj$.

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- Only the scalar sector in this model is explored in detail, it would be interesting to study whether new phenomenology would arise when we include the composite vector resonances.