Higgs physics in the Composite models

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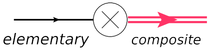
Composite pseudo Nambu Goldstone Higgs

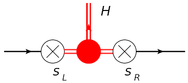
- Models where Higgs is a composite state give natural solution to the hierarchy problem
- Higgs can be made naturally light if it is Pseudo Nambu Goldstone Boson(PNGB) (*Georgi, Kaplan; Giudice,Grojean,Pomarol,Rattazzi*)
- This scenario is realized in the warped extra dimensional models (*Randall,Sundrum*)with gauge-higgs unification Higgs arises as a 5th component of the 5D gauge field
- EWPT $\Delta\rho$ requires that the symmetry breaking structure should be $SU(2)_L \times SU(2)_R/SU(2)_V$
- The minimal construction with custodial symmetry is realized in $SO(5) \to SO(4)$(*Contino, Agashe, Pomarol*)

Fermions: Partial compositeness

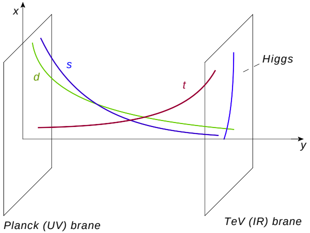
- SM fermions mix only linearly with composite fermions (partial compositeness mechanism *(Kaplan)*)



- Fermion mass generation



- 5D picture

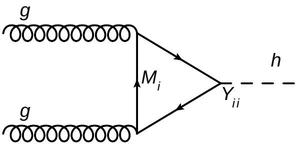


$$s_{L,R} \Leftrightarrow f(\text{IR brane})$$

The Model

- Higgs is a PNGB (we will consider only $SO(5)/SO(4)$ cosets)
- SM fermion masses are generated by partial compositeness mechanism
- Couplings that are important for LHC: $hWW, hZZ, h\gamma\gamma, hgg, hbb, htt$
- hWW, hZZ rescaled by $\sqrt{1 - v_{SM}^2/f^2}$
- What about modifications of the $hgg, h\gamma\gamma, hbb, htt$ couplings? $t_{L,R}$ mixes strongly with composite sector and we might expect strong dependence on the masses of the lightest composite partners. (*Falkowski;Low,Rattazzi,Vichi;Low,Vichi*)

Simple trick to calculate the Hgg coupling

- 

$\sim hG_{\mu\nu}G^{\mu\nu}$

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$$\delta Hgg \propto \sum_{M_i > m_H} \frac{Y_{ii}}{M_i} = \sum_i \frac{Y_{ii}}{M_i} - \sum_{M_i < m_H} \frac{Y_{ii}}{M_i}$$
$$\mathrm{tr}(YM^{-1}) - \sum_{M_i < m_H} \frac{Y_{ii}}{M_i} = \frac{\partial \log(\det M)}{\partial v} - \sum_{M_i < m_H} \frac{Y_{ii}}{M_i}$$

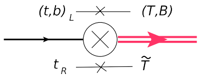
(Ellis,Gaillard,Nanopoulos;Shifman,Vainshtein,Voloshin,Zakharov)

- In the SM only top contributes to the Hgg coupling so the coupling is given by $\frac{1}{v}$. For the generic model we just need to calculate determinant of the mass matrix.

Single **5** model

- We will use two site description with just one composite multiplet of $SO(5)$

$$\mathcal{Q} = \frac{1}{\sqrt{2}} \begin{pmatrix} \chi_{5/3} + B_{-1/3} \\ i(\chi_{5/3} - B_{-1/3}) \\ T_{2/3} + T'_{2/3} \\ i(T_{2/3} - T'_{2/3}) \\ \sqrt{2}\tilde{T}_{2/3} \end{pmatrix}$$



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$$\Delta\mathcal{L} = \lambda_q \bar{q}_L P_q \xi^\dagger \mathcal{Q}_R + \lambda_t \bar{t}_R P_t \xi^\dagger \mathcal{Q}_L + Y_* f(\bar{\mathcal{Q}}_R \Sigma_0)(\Sigma_0^\dagger \mathcal{Q}_L) + M_5 \bar{\mathcal{Q}}_R \mathcal{Q}_L$$
$$\Sigma_0 \equiv (0,0,0,0,1), \quad \xi \equiv \exp[\sqrt{2} T^4 h/f]$$

Hgg in the model

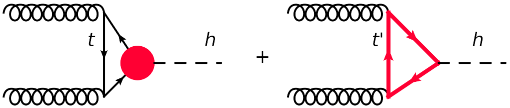
- $$\Delta\mathcal{L} = \lambda_q \bar{q}_L P_q \xi^\dagger \mathcal{Q}_R + \lambda_t \bar{t}_R P_t \xi^\dagger \mathcal{Q}_L + Y_* f (\bar{\mathcal{Q}}_R \Sigma_0)(\Sigma_0^\dagger \mathcal{Q}_L) + M_5 \bar{\mathcal{Q}}_R \mathcal{Q}_L$$

- $$M_t = \begin{pmatrix} 0 & \frac{\lambda_q(\cos(v/f)+1)}{2} & \frac{\lambda_q(\cos(v/f)-1)}{2} & \frac{i\lambda_q \sin(v/f)}{\sqrt{2}} \\ \frac{-i\lambda_t^* \sin(v/f)}{\sqrt{2}} & M_5 & 0 & 0 \\ \frac{-i\lambda_t^* \sin(v/f)}{\sqrt{2}} & 0 & M_5 & 0 \\ \lambda_t^* \cos(v/f) & 0 & 0 & M_5 + Yf \end{pmatrix}$$
$$\det M_t \propto \sin \frac{2v}{f}$$

- $$\frac{\partial \log(\det M_t)}{\partial v} = \frac{2}{f} \cot\left(\frac{2v}{f}\right) \simeq \frac{1}{v_{SM}} \left(1 - \frac{3}{2} \frac{v_{SM}^2}{f^2}\right)$$
$$v_{SM} = f \sin \frac{v}{f}$$

- No dependence on mixing parameters λ, mass of top custodian partner M_5 !

Hgg coupling



- Total contribution is the sum of the diagram with SM top and diagrams with t'.
- What about SM top Yukawa ?

Top Yukawa coupling

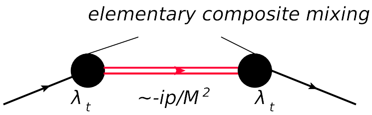
- Field redefinition

$$Q^{CCWZ} \equiv \xi Q,\ \ \Sigma = (0,0,0,\sin(\tfrac{h}{f}),\cos(\tfrac{h}{f}))$$
$$\Delta\mathcal{L} = \lambda_q \bar{q}_L P_q \mathcal{Q}_R + \lambda_t \bar{t}_R P_t \mathcal{Q}_L + Y_* f(\bar{\mathcal{Q}}_R \Sigma)(\Sigma^\dagger \mathcal{Q}_L) + M_5 \bar{\mathcal{Q}}_R \mathcal{Q}_L$$

- If we promote λ couplings to spurions of $SU(2) \times U(1) \times SO(5)$ we can see that, we can parameterize effects of the heavy composite states in terms of the operators

$$\hat{\lambda}_i \mapsto O^\dagger_{SU(2)_L \times U(1)_Y} \hat{\lambda}_i \mathcal{G} \Rightarrow\ \bar{q}_L \left(\hat{\lambda}_q \Sigma^\dagger\right)\left(\Sigma \hat{\lambda}_t^\dagger\right) t_R \propto \sin(2v/f)$$
$$\bar{q}_L \partial\!\!\!/ q_L \left|\hat{\lambda}_q^\dagger \Sigma\right|^2,\ \ \bar{t}_R \partial\!\!\!/ t_R \left|\hat{\lambda}_t^\dagger \Sigma\right|^2$$

Top Yukawa coupling

- 

$\Rightarrow \bar{t}\not\partial t \left(\mathcal{O}(\lambda H/(fM_5))^2\right)$

- $$Z_t \sim \left[1 + |\lambda_t|^2 \left(\frac{\sin^2(v/f)}{M_5^2} + \frac{\cos^2(v/f)}{(M_5+Yf)^2}\right)\right]$$
$$m \to \frac{m}{\sqrt{Z_q}\sqrt{Z_t}} \sim \frac{y_t f}{2}\sin(2v/f)\left[1 - \frac{|\lambda_t|^2}{2}\left(\frac{\sin^2(v/f)}{M_5^2} + \frac{\cos^2(v/f)}{(M_5+Yf)^2}\right)\right] + \dots$$

- unlike *Hgg*, top Yukawa strongly depends on the masses of the top partners

Top yukawa coupling

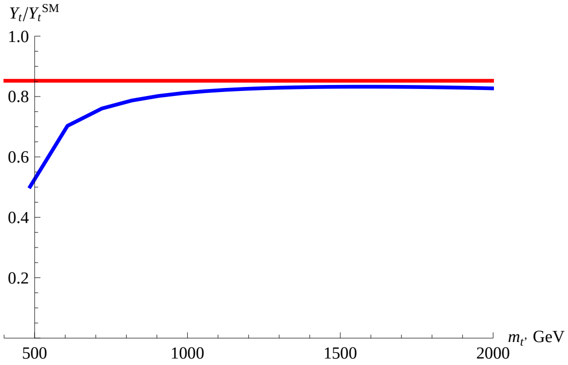
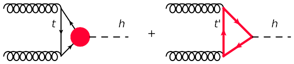


Figure : Modification of the top Yukawa coupling as a function of $m_{t'}$, $Y = 3$, f=800 GeV, red line trigonometric rescaling

Hgg vs y_t in the model with **5**

- Top Yukawa coupling strongly depends on the masses of the composite partners
- Overall Hgg depends only on the $\frac{v}{f}$ parameter
- Contribution of the diagrams with t and t' to Hgg sum up to give simple trigonometric rescaling of the Hgg coupling



$\frac{2}{f}\frac{\cos\frac{2v}{f}}{\sin\frac{2v}{f}}$ vs $\frac{1}{v^{SM}}$ in SM

- Is it always the case? What about contributions of the b', χ'

Determinant properties

- $$\det M_t \propto \lambda_q \lambda_t^*$$

  No terms with higher powers of $\lambda_{q,t}$

- $$\lambda_q \bar{q}_L P_q \mathcal{Q}_R + \lambda_t \bar{t}_R P_t \mathcal{Q}_L$$

  promote λ mixing parameters which explicitly break global $SO(5)$ to the spurions which transform under $U(1)_{EM} \times SO(5)$

  $$\hat{\lambda}_i \mapsto e^{-i\alpha q_i} \cdot \hat{\lambda}_i \cdot \mathcal{G},$$

Determinant properties

- Determinant should be $SO(5) \times U(1)_{EM}$ invariant

$$\det M_t = (\Sigma^\dagger \hat{\lambda}_q^t)(\hat{\lambda}_t^\dagger \Sigma) \cdot P(M_*, Y_*, f),$$

v/f dependence is factorized, in the model with **5** we get

$$\det M_t \propto (\Sigma^\dagger \hat{\lambda}_q^t)(\hat{\lambda}_t^\dagger \Sigma) = \sin \frac{2v}{f}$$

- Is it always the case?

Determinant properties

- $t_L(t_R)$ mixes more than with one operator

$$\lambda_q \bar{q}_L P_q \xi^\dagger \mathcal{Q}_R \to \sum_i \lambda_q^{(i)} \bar{q}_L P_q \xi^\dagger \mathcal{Q}_R^{(i)}$$

  for example t_L mixes with **10** and **5** and t_R mixes with **10**
- $\hat{\lambda}_q \to (\hat{\lambda}_q^{(5)}, \hat{\lambda}_q^{(10)})$
-

$$\det M = \left(\Sigma^\dagger \hat{\lambda}_q^{(10)} \left(\hat{\lambda}_t^{(10)}\right)^\dagger \Sigma\right) \cdot P_1(M_*, Y_*) + \left(\Sigma^\dagger \lambda_t^{(10)} \left(\hat{\lambda}_q^{(5)}\right)^\dagger\right) \cdot P_2(M_*, Y_*),$$

$$\left(\Sigma^\dagger \hat{\lambda}_q^{(10)} \left(\hat{\lambda}_t^{(10)}\right)^\dagger \Sigma\right) \propto \sin(2v/f) \quad \text{and} \quad \left(\Sigma^\dagger \lambda_t^{(10)} \left(\hat{\lambda}_q^{(5)}\right)^\dagger\right) \propto \sin(v/f).$$

- v/f dependence is not factorized any more

Example Model **10,5**

- q_L mixes with **10**, **5** operators, t_R- with **10**

$$\Delta\mathcal{L}_{10+5} = \bar{t}_R^{SM}\mathrm{tr}\left(\left(\hat{\lambda}_t^{(10)}\right)^\dagger \mathcal{Q}_L\right) + \mathrm{tr}(\bar{\mathcal{Q}}_R\hat{\lambda}_q^{(10)})q_L^{SM} + (\bar{\mathcal{T}}_R\hat{\lambda}_q^{(5)})q_L^{SM}$$

-

$$\det M_t \propto \lambda_t^{(10)} \sin\left(\tfrac{v}{f}\right)\left(\sqrt{2}fM_{10}\tilde{Y}_5\lambda_q^{(5)} - \cos\left(\tfrac{v}{f}\right)\left(f^2 Y_5\tilde{Y}_5 + fM_5 Y_{10}\right)\lambda_q^{(10)}\right).$$

- if $\tilde{Y}_5 f = Y_5 f = Y_{10} f = M_5 = M_{10}$

$$\frac{\partial \log \det M_t}{\partial v} \propto \frac{1}{v_{SM}}\left[1 + \left(\frac{6\lambda_q^{(10)} - \sqrt{2}\lambda_q^{(5)}}{\sqrt{2}\lambda_q^{(5)} - 2\lambda_q^{(10)}}\right)\frac{v_{SM}^2}{6f^2}\right],$$

- If $\sqrt{2}\lambda_q^{(10)} < \lambda_q^{(5)} < 3\sqrt{2}\lambda_q^{(10)}$ the coupling Hgg increases, otherwise it is reduced.

Model with **14**

- If t_R mixes with **14** and t_L mixes with **5** there are two types of Yukawa couplings

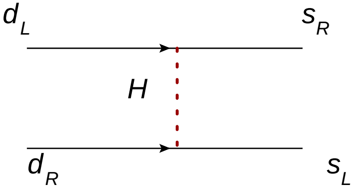
$$\hat{\lambda}_t^{14} \to \mathbf{14},\ \ \hat{\lambda}_q^{5} \to \mathbf{5}$$

$$(\Sigma\hat{\lambda}_t^{14}\Sigma)(\Sigma\hat{\lambda}_q^{5}) \propto \sin(v/f)\left(1 - 5\cos^2(v/f)\right),$$

$$(\Sigma\hat{\lambda}_t^{14}\hat{\lambda}_q^{5}) \propto \sin(v/f)$$

t' effects

- We can get very nontrivial modifications of the Hgg in the case when SM $t_L(t_R)$ quark mixes with different representations of the composite fermions
- If these operators are present in the light quark sectors, we have strong constraints from the Higgs mediated flavor violation



(Agashe,Contino)

b' and χ effects

- What about $\chi_{5/3}$ effects?
  - Hgg coupling $\propto (H^\dagger H) G_{\mu\nu} G^{\mu\nu}$ explicitly violates Goldstone symmetry, so it must be proportional to the explicit symmetry breaking parameters
  - $\chi_{5/3}$ does not mix with elementary fermions, so cannot contribute to this coupling.
  - Contribution of the partners of the light generations will be suppressed.
- b'?
  - Naively contribution should be suppressed by the m_b i.e. very small
  - In the models where $(t, b)_L$ is fully composite this is not the case, we might expect large effects from b'

Hgg from b'

$$\Delta Hgg \propto \sum_{M_i > m_H} \frac{Y}{M_i} = \frac{\partial \log(\det M_b)}{\partial v} - \frac{y_b}{m_b},$$

$$\det M_b \propto F(v/f)$$

$$\frac{y_b}{m_b} \approx \frac{F'(v/f)}{f} + \frac{1}{v} \cdot \mathcal{O}\left(\frac{\lambda_q^2 v^2}{f^2 M_*^2}\right)$$

$$\frac{\partial \log(\det M_b)}{\partial v} = \frac{F'(v/f)}{f}$$

$$\Delta Hgg \propto -\frac{1}{v}\mathcal{O}\left(\frac{\lambda_q^2 v^2}{f^2 M_*^2}\right)$$

- If b_L is fully composite $\frac{\lambda_q}{M_*} \to$ large, we will get large corrections to the Hgg coupling from b'
- Modifications of the Hgg and y_b couplings go in the opposite directions

Numerical results

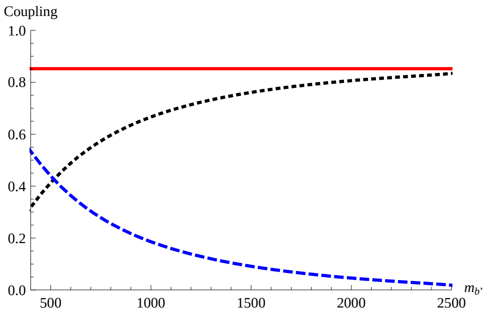


Figure : Couplings in the model with **10,10,5**, $M_* = 3.2$ TeV, $f = 800$ GeV, $Y_* = 3$, black dashed bottom Yukawa coupling, blue dashed contribution of the b' to the Hgg coupling

$Z\bar{b}b$ and V_{tb} constraints

- Light b' potentially problematic for the $Z\bar{b}b$ and V_{tb} constraints
- $\frac{\delta g_{Zbb}}{g_{Zbb}} \lesssim 2 \cdot 10^{-3}$
  $Z\bar{b}b$ is protected by custodian representations of the fermions
  (Agashe,Contino,Da Rold,Pomarol)
- $|V_{tb}| \gtrsim 0.77$ (Tevatron), if $f = 800$ GeV, $Y_* = 3$ we need $m_{b'} \gtrsim 470$ GeV, roughly in the same ballpark as recent collider constraints from LHC on the masses of the $t' \gtrsim 560$, $b' \gtrsim 600$ GeV (assuming 100% $Br(t' \to bW)$)

The $(\mathbf{10}, \mathbf{10}, \mathbf{5})$ Model

- t_R mixes with **5**, b_R mixes with **10**, (t_L, b_L) mixes with **10**

$$\mathcal{L}_{mixing} \sim \bar{t}_R^{SM}(\hat{\lambda}_t^{\dagger}\mathcal{T}_L^5) + \bar{b}_R^{SM}\,\mathrm{tr}\left(\hat{\lambda}_b\mathcal{B}_L^{10}\right) + \mathrm{tr}(\bar{\mathcal{Q}}_R^{10}\hat{\lambda}_q)q_L^{SM}$$

-

$$\det M_t \propto (\Sigma^{\dagger}\hat{\lambda}_q^t\hat{\lambda}_t) \propto \sin\left(\frac{v}{f}\right)$$

t, t' contribution is suppressed, b' contribution is important

$\gamma\gamma$ signal modification

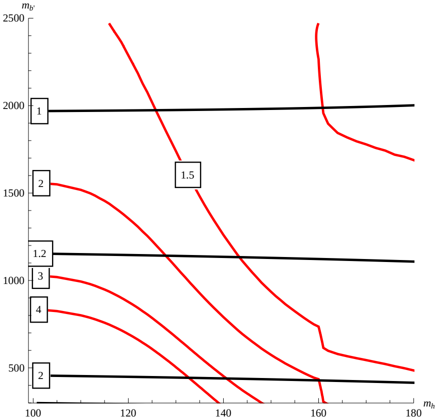
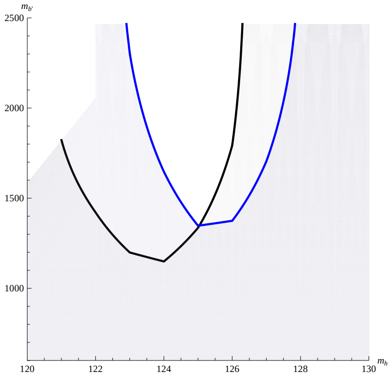


Figure : Contour plots for the rescaling of the $\sigma(gg \to H)$ and $\sigma(gg \to H) \times \mathrm{BR}(H \to \gamma\gamma)$.

Summary

- We discussed the structure of the Higgs couplings in the Composite Higgs models
- We have shown that in the presence of light t' Hgg and Htt are independent parameters
- We identified conditions when contributions of t' can increase the overall rate of the gluon fusion
- Effects of light b' are generically important, and they can also enhance the rate of the gluon fusion

ATLAS and CMS constraints, 5 fb^{-1}



Bounds are derived using "Gaussian" combination (AA,Contino,Galloway)