New Prospects for Higgs Compositeness in $h \to Z\gamma$

Aleksandr Azatov

CERN

HEFT 2013

(A.A, R.Contino, A. Di Iura, J,Galloway) arXiv:1308.2676

Composite Higgs setup

- Models where Higgs is a composite state give natural solution to the hierarchy problem
- Higgs must be lighter than the rest of the composite resonances , this can be achieved if it is a PNGB (*Georgi, Kaplan; Giudice,Grojean,Pomarol,Rattazzi*)
- 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 $SO(5) \rightarrow SO(4)$(*Contino, Agashe, Pomarol*)

Operators contributing to the $h \to Z\gamma$ coupling

- SILH Lagrangian, parametrizes effects of new physics in terms of the higher dimensional operators, the operators relevant for the $h\gamma\gamma, hZ\gamma$ interactions are

$$O_{HW} = \frac{ig}{m_W^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu}, \quad O_{HB} = \frac{ig'}{m_W^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$O_{BB} = \frac{g'^2}{m_W^2}(HH^\dagger) B_{\mu\nu} B^{\mu\nu}$$

- O_{BB} is contributing to the $h\gamma\gamma, hZ\gamma$. O_{HW}, O_{HB} contribute to the $hZ\gamma$
- Effective Lagrangian in terms of the Z, γ fields

$$\mathcal{L} = \frac{c_{\gamma\gamma}}{2}\gamma_{\mu\nu}\gamma^{\mu\nu}\frac{h}{v} + c_{z\gamma} Z_{\mu\nu}\gamma^{\mu\nu}\frac{h}{v}$$
$$c_{\gamma\gamma} = 8\sin^2\theta_w c_{BB},$$
$$c_{Z\gamma} = -\tan\theta_w \left((c_{HW} - c_{HB}) + 8\sin^2\theta_w c_{BB}\right)$$

Estimating the size of the operators

- $$O_{HW} = \frac{ig}{m_W^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu}, \quad O_{HB} = \frac{ig'}{m_W^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$O_{BB} = \frac{g'^2}{m_W^2}(HH^\dagger) B_{\mu\nu} B^{\mu\nu}$$

- By simple dimensional analysis $c_{HW,HB} \sim \frac{m_w^2}{M^2}$ so that
$$\frac{\Delta\Gamma_{HW,HB}}{\Gamma^{SM}} \sim \frac{16\pi^2 v^2}{M^2}$$

- O_{BB} violates Goldstone symmetry of the Higgs boson $\Rightarrow$ $c_{BB} \sim \frac{m_w^2}{M^2} \times \left(\frac{\lambda}{M}\right)^2$
$$\frac{\Delta\Gamma_{BB}}{\Gamma^{SM}} \sim \frac{16\pi^2 v^2}{M^2} \times \frac{\lambda^2}{M^2}$$

Symmetry properties of $hZ\gamma$ interaction

- Ignoring O_{BB}

$$\mathcal{L}_{SILH} = \frac{ig}{m_W^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{ig'}{m_W^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \Rightarrow$$
$$\mathcal{L}_{Z\gamma} = -\tan\theta_w (c_{HW} - c_{HB}) Z_{\mu\nu}\gamma^{\mu\nu}\frac{h}{v}$$

- $hZ\gamma$ interaction is proportional $c_{HB} - c_{HW}$, symmetry reason?

Symmetry properties of $hZ\gamma$ interaction

- Composite sector must be invariant under $SU(2)_L \times SU(2)_R$ symmetry because of the $\Delta\rho$ constraints
- SM B_μ couples to the T_R^3 of the composite sector.
- $Z \sim B - W_3^L, \quad A \sim B + W_3^L \Rightarrow$ we can introduce the spurious symmetry P_{LR} under, which $L \Leftrightarrow R$

$$Z \Leftrightarrow -Z, \quad A \Leftrightarrow A, \quad < H > \Leftrightarrow < H >$$

  Higgs vev $< H >$ is invariant because it has vev along the $(\pm 1/2, \mp 1/2)$ components, $hZ\gamma$ interaction violates P_{LR}
- $P_{LR} : O_{BH(WH)} = O_{WH(BH)}$ and $(O_{BH} - O_{WH})$ is P_{LR} odd operator

Symmetry properties of $hZ\gamma$ interaction

- Composite sector must be invariant under $SU(2)_L \times SU(2)_R$ symmetry because of the $\Delta\rho$ constraints
- SM B_μ couples to the T^3_R of the composite sector.
- $Z \sim B - W^L_3, \quad A \sim B + W^L_3 \Rightarrow$ we can introduce the spurious symmetry P_{LR} under, which $L \Leftrightarrow R$

$$Z \Leftrightarrow -Z, \quad A \Leftrightarrow A, \quad < H > \Leftrightarrow < H >$$

  Higgs vev $< H >$ is invariant because it has vev along the $(\pm 1/2, \mp 1/2)$ components, $hZ\gamma$ interaction violates P_{LR}
- $P_{LR} : O_{BH(WH)} = O_{WH(BH)}$ and $(O_{BH} - O_{WH})$ is P_{LR} odd operator
- SM Yukawa couplings, gauging of $SU(2)_L$ and $U(1)_Y$ break P_{LR}, $hZ\gamma$ is generated

$hZ\gamma$ in CCWZ language ($SO(5)/SO(4)$ example)

- CCWZ construction allows to write down lagrangian for nonlinearly realized symmetry breaking $\mathcal{G}/\mathcal{H}$
- Goldstone bosons of spontaneous symmetry breaking can be parametrized by the field

$$U(\Pi) = e^{i\Pi}, \quad \Pi = \Pi^{\hat{a}} T^{\hat{a}}$$

and by the Maurer-Cartan form

$$-iU^\dagger \partial_\mu U = d_\mu^{\hat{a}} T^{\hat{a}} + E_\mu^a T^a \equiv d_\mu + E_\mu$$

$$d_\mu^{\hat{a}} = A_\mu^{\hat{a}} + \frac{\sqrt{2}}{f}(D_\mu \pi)^{\hat{a}} + O(\pi^3)$$

$$E_\mu^a = A_\mu^a - \frac{i}{f^2}(\pi \overleftrightarrow{D}_\mu \pi)^a + O(\pi^4)$$

List of operators in CCWZ

We can expand our effective lagrangian in number of derivatives since from NDA every derivative is suppressed by the power of a cut-off $\frac{\partial_\mu}{\Lambda}$

- $O(p^2)$- $O_1 = f^2 Tr(d_\mu d^\mu) \Leftrightarrow W_\mu W^\mu \sin^2(\frac{h}{f})$
- $O(p^4)$ lagrangian (*Rattazzi,Contino, Pappadopulo,Marzocca*)

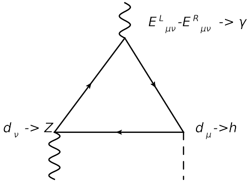
$$O_3^\pm = Tr(E^L_{\mu\nu} E^L_{\mu\nu}) \pm Tr(E^R_{\mu\nu} E^R_{\mu\nu}),$$
$$O_4^\pm = Tr(E^L_{\mu\nu} \pm E^R_{\mu\nu}) i[d_\mu, d_\nu], \qquad O_4^- \to \partial_\nu h Z_\mu \gamma_{\mu\nu} \text{ interaction}$$
$$\mathcal{O}(d^4) \Leftrightarrow \text{dim 8 operators}$$

- P_{LR} properties

$$E_{L,R} \to P_{LR} E_{R,L} P_{LR}, \quad P_{LR} = Diag(-1,-1,-1,1,1)$$
$$d \to P_{LR}\ d\ P_{LR}$$

O_4^-

- $O_4^- = iTr(E^L_{\mu\nu} - E^R_{\mu\nu})[d_\mu, d_\nu])$
- Higgs comes from the covariant derivative, $\partial_\mu h$ so this coupling will have no Goldstone suppression
- Composite sector must violate P_{LR} in order to generate O_4^-
- from NDA $hZ\gamma$ is log divergent?

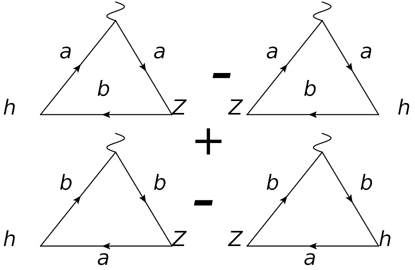


Derivative couplings/absence of log divergence

It is useful to look at the $U(1)_V$ subgroup of SO(4)

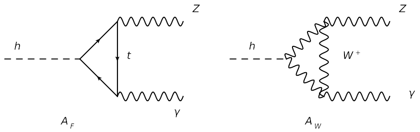
$$\mathcal{L}_{Z\gamma} = \sum_{a,b} \left[\frac{\partial_\mu h}{f} \lambda^h_{ab} \bar{\psi}_a \gamma^\mu \psi_b + \lambda^Z_{ab} Z_\mu \bar{\psi}_a \gamma^\mu \psi_b + q_\psi \delta_{ab} A_\mu \bar{\psi}_a \gamma^\mu \psi_b \right]$$

- Loop function is antisymmetric in μ, ν(higgs and Z indices)$\Rightarrow$ Amplitude $\sim Tr(\lambda^h \lambda^Z) - Tr(\lambda^Z \lambda^h) = 0$
- we need at least one mass insertion$\Rightarrow$ no log divergence



$Z\gamma$ coupling in the SM

- This decay is generated by the loops of $W^{\pm}$ and t

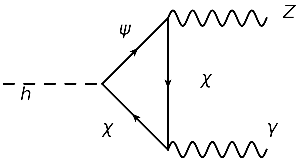


- $\Gamma(h \to Z\gamma) = \frac{1}{32\pi}|A|^2 m_h^2 \left(1 - \frac{m_Z^2}{m_h^2}\right)^3 A = \frac{\alpha g}{4\pi m_w}(A_F + A_W)$.
  The SM loop is dominated by the contribution of W, $A_W/A_F \sim -18$
- top contribution is suppressed because top coupling to Z is small
  $T_Z \sim T_L^3 - 2q_t \sin^2\theta \sim 0.2$, so new fermions can be very important

$hZ\gamma$ vs $h\gamma\gamma$

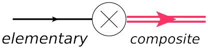
What is the difference between $h\gamma\gamma$ and $hZ\gamma$ loops?

- Not all the fermions have the same couplings to Z
- Z can couple to two different mass eigenstates, so in the loop we can have two different fermions

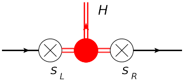


Fermions: Partial compositeness (Kaplan)

- SM fermions mix only linearly with composite fermions



- Fermion mass generation



need separate composite partner for each SM fermion

- We have a large multiplicity of the composite states at the scale of a few TeV $\sim N_F \times D$

Model with 5

- under $SU(2)_L \times SU(2)_R$: $\mathbf{5} = (2,2) + 1$, the breaking of the SO(5) does not break $P_{LR} \Rightarrow$ no $hZ\gamma$ in the absence of the elementary composite mixing
- top Yukawa coupling breaks down P_{LR} so these effects will be suppressed by $O\left(\frac{\lambda^2}{M_*^2}\frac{v^2}{f^2}\right)$, however in the SM top contribution is much smaller than the W contribution.

$$A_{SM} \sim A_W \sim 20 A_{top}$$

corrections from t' in the loops will be of the order of $\lesssim 0.05\frac{v^2}{f^2}$

- modification is dominated by the trigonometric rescaling of the W coupling, $A_5 \approx A_{SM}\sqrt{1 - v^2/f^2}$

Model with 10

- under $SU(2)_L \times SU(2)_R$: $10 = (2,2) + (3,1) + (1,3)$
- Different masses and interactions of $(3,1)$ and $(1,3)$ respect $SU(2)_L \times SU(2)_R$ but break P_{LR}
- Ignore elementary composite mixing

$$\mathcal{L} = m_4 \bar{4} 4 + m_{(3,1)} (3,1)^* (3,1) + m_{(1,3)} (1,3)^* (1,3)$$
$$+ \overline{10} (\not{\partial} - \not{E}) 10 - \zeta_{13} \bar{4} \not{d} (1,3) - \zeta_{31} \bar{4} \not{d} (3,1).$$

Model with 10

- At one loop $O_{Z\gamma}$ is generated with the coefficient

$$C_{Z\gamma} \sim \frac{g^2}{4}\sin^2\theta \left[|\zeta_{13}|^2 \left(C(m_4, m_{(1,3)}) - C(m_{(1,3)}, m_4) \right) - |\zeta_{31}|^2 \left(C(m_4, m_{(3,1)}) - C(m_{(3,1)}, m_4) \right) \right]$$

- If we look at the ratio of the new physics effects to the contribution of the SM top in the limit $\Delta m \ll m$ we will get

$$\frac{\text{NP}}{\text{SM top}}\Big|_{\Delta m \ll m} \sim 15 N_{gener} \times \left(\frac{v}{f}\right)^2 \frac{\Delta m}{m}$$

P_{LR} vs $Z\bar{b}b$ constraints

- Large modification to the $hZ\gamma$ requires P_{LR} breaking in the composite sector.
- In order to reproduce the top mass, electroweak doublet $q_L = (t_L, b_L)$ must mix strongly with the composite sector. $Z\bar{b}b$ constraints require b_L to mix strongly only with the operator which respects P_{LR} (*Agashe,Contino, Pomarol,DaRold*) in MCHM5 $(b_L - B(1/2, 1/2)))$
- Model with **5** has an accidental P_{LR} (*Contino,Rattazzi,Pappadopulo,Marzocca*) symmetry due to the fact that

$$\mathbf{5} = \mathbf{1} + (\mathbf{2}, \mathbf{2})$$

$SO(5)/SO(4)$ breaking cannot split masses inside $(\mathbf{2}, \mathbf{2})$

Constructing realistic model with P_{LR} breaking

- $q_L = (t, b)_L$ must mix with **5** in order to be protected from $Z\bar{b}b$
- Take MCHM5 but mix b_R with **10** instead of **5**

Minimal $\not{P}_{LR}$ model $10 + 5$

$q_L \overset{\lambda_q^{10}}{- - -} 10 - -10 \overset{\lambda_b}{- - -} b_R \Rightarrow$	$m_b \sim \lambda_q^{10} \lambda_b$
$q_L \overset{\lambda_q^{5}}{- - -} 5 - -5 \overset{\lambda_t}{- - -} t_R \Rightarrow$	$m_t \sim \lambda_q^{5} \lambda_t$

$\lambda_q^{10} \ll \lambda_q^5$, $Z\bar{b}b$ is fine

$$\mathcal{L}_{mixing} = \lambda_q^{10} \bar{q}_L P_q 10 + \lambda_q^5 \bar{q}_L P_q 5 + \lambda_b \bar{b}_R P_b 10 + \lambda_t \bar{t}_R P_t 5$$

Forbid mixing between 10 and 5 imposing different $U(1)_X$ charges

Model with 10, numerical calculation

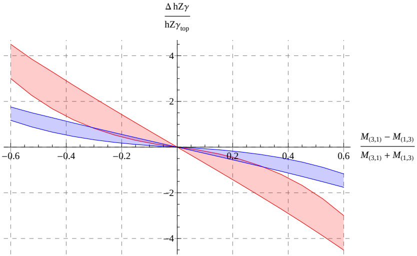


Figure: ratio of the A_{NP}/A_{top} for the model with 10 for one generation, red $f = 500$, blue $f = 800$ GeV

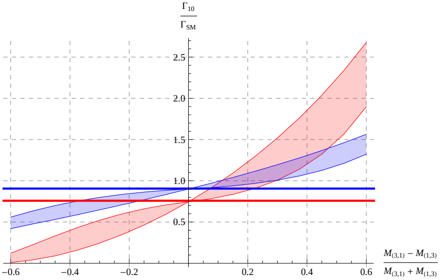
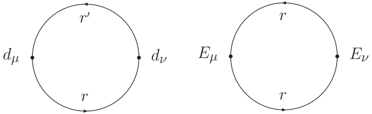


Figure: ratio of the Γ_{NP}/Γ_{SM} in the model with 10 with three generations

Contribution to the S parameter

- Corrections to the S parameter will be generated by the loop of the composite particles, no elementary composite mixing is necessary (Golden,Randall;Barbieri,Isidori,Pappadopulo; Grojean, Matsedonskyi,Panico;AA,Contino,Di Iura,Galloway)



$$\mathcal{L} = \sum_r \bar{\chi}_r (i \nabla\!\!\!/ - m_r)\chi_r - \zeta_{rr'} \chi_r d\!\!\!/ \chi_{r'}$$

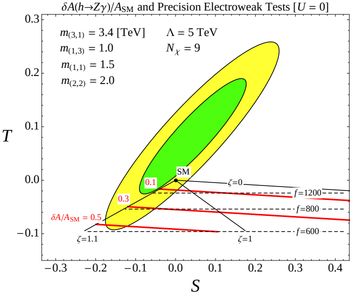
$$\Delta S = -\frac{8\pi}{gg'} \sin^2\theta \left[-\Pi'_{\hat{3}\hat{3}} + \frac{1}{2}\Pi'_{3L3L} + \frac{1}{2}\Pi'_{3R3R} \right]$$

$$\Delta S \simeq \frac{N_\chi \sin^2\theta}{3\pi} \left(1 - |\zeta|^2\right) \log\frac{\Lambda^2}{m^2} + \text{finite}$$

- ΔS is finite when $\zeta = 1$, because in this limit we can remove derivative Higgs interactions by the fermion field redefinition.

Contribution to the S parameter

- S parameter is given by the operator $O_3^+ = Tr(E^L_{\mu\nu}E^L_{\mu\nu}) + Tr(E^R_{\mu\nu}E^R_{\mu\nu})$, no P_{LR} violation is required, generically O_4^- and O_3^+ are independent
- However assuming no cancellations between different contributions we can loot at the correlation between ΔS and $\delta A(h \to Z\gamma)$
- The fermion contribution to the S parameter can be of both signs, and the negative sign contribution can relax the current constraints from EWPT.



Outlook

- We studied $hZ\gamma$ in the Composite Higgs models
- $h \to Z\gamma$ decay receives large new physics corrections that are not suppressed by the Goldstone symmetry arguments.
- Contribution of the strong dynamics to the $h \to Z\gamma$ is controlled by the P_{LR} breaking. If the modification of the $Z\bar{b}b$ coupling is isolated from the P_{LR} breaking, viable model can be constructed with $O(1)$ modification of the $h \to Z\gamma$ decay.
- Similar processes lead to the contribution to the S parameter. Negative ΔS can relax the current EWPT bounds and at the same time accommodate large $h \to Z\gamma$

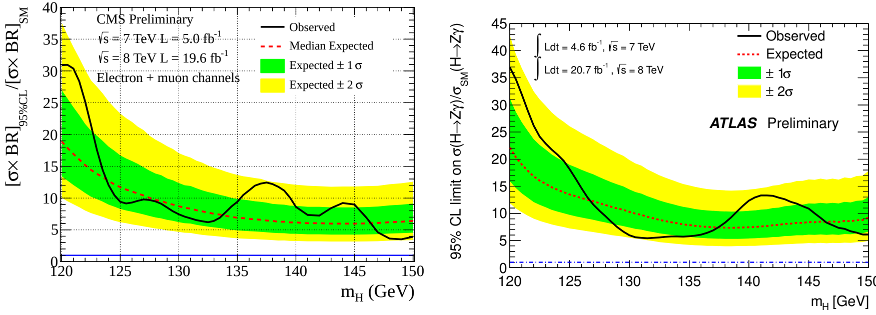
$hZ\gamma$ from integrating out ρ

- minimal CCWZ lagrangian for the vector ρ with an additional operator Q_1

$$\mathcal{L} = -\frac{1}{4g_{\rho_L}}^2 Tr(\rho^L_{\mu\nu}\rho^{L,\mu\nu}) + \frac{m^2_{\rho L}}{2g^2_{\rho L}} Tr(\rho^L_\mu - E^L_\mu)^2$$
$$+\alpha^L_1 Tr(\rho^{\mu\nu}_L i[d_\mu d_\nu]) + (L \Leftrightarrow R)$$

- Integrating out ρ at tree level we will get

$$c_{Z\gamma} = \frac{g^2}{2}\sin^2\theta(\alpha^L_1 - \alpha^R_1)$$



CMS Preliminary
√s = 7 TeV L = 5.0 fb-1
√s = 8 TeV L = 19.6 fb-1
Electron + muon channels
Observed
Median Expected
Expected ± 1 σ
Expected ± 2 σ
[σ× BR]95%CL/[σ× BR]SM
mH (GeV)
∫ Ldt = 4.6 fb-1, √s = 7 TeV
∫ Ldt = 20.7 fb-1, √s = 8 TeV
Observed
Expected
± 1σ
± 2σ
ATLAS Preliminary
95% CL limit on σ(H→Zγ)/σSM(H→Zγ)
mH [GeV]