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

Aleksandr Azatov

CERN

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(A.A, R.Contino, A. Di Iura, J,Galloway) arXiv:1308.2676
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 $h \rightarrow Z\gamma$ 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 $Z, \gamma$ 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 $O_{BB}$

$$\mathcal{L}_{\text{SILH}} = \frac{ig}{m_W^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{ig'}{m_W^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \Rightarrow$$

$$\mathcal{L}_{Z\gamma} = -\tan \theta_W (c_{HW} - c_{HB}) Z_{\mu\nu} \gamma^{\mu\nu} \frac{h}{v}$$

- $hZ\gamma$ 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 $B_\mu$ couples to the $T^3_R$ of the composite sector.
- $Z \sim B - W^L_3$, $A \sim B + W^L_3 \Rightarrow$ 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
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- $P_{LR} : O_{BH(WH)} = O_{WH(BH)}$ 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.
CCWZ construction allows to write down lagrangian for nonlinearly realized symmetry breaking $G/H$

Goldstone bosons of spontaneous symmetry breaking can be parametrized by the field

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

and by the Maurer-Cartan form

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

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

$$E_\mu^a = A_\mu^a - \frac{i}{f^2} (\pi \leftrightarrow D_\mu \pi)^a + O(\pi^4)$$
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 $\frac{\partial \mu}{\Lambda}$

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

$$O_{3}^{\pm} = \text{Tr}(E^L_{\mu\nu}E^L_{\mu\nu}) \pm \text{Tr}(E^R_{\mu\nu}E^R_{\mu\nu}),$$

$$O_{4}^{\pm} = \text{Tr}(E^L_{\mu\nu} \pm E^R_{\mu\nu})i[d_\mu, d_\nu], \quad O_4^- \to \partial_\nu hZ_\mu \gamma_{\mu\nu} \text{ interaction}$$

$O(d^4) \iff$ dim 8 operators

- $P_{LR}$ properties

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

$$d \to P_{LR} \, d \, P_{LR}$$
$O_4^- = i \text{Tr}(E_{\mu\nu}^L - E_{\mu\nu}^R)[d_\mu, d_\nu])$

- 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)

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

- Loop function is antisymmetric in $\mu, \nu$ (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
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.
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 $SU(2)_L \times SU(2)_R$: $5 = (2, 2) + 1$, the breaking of the SO(5) does not break $P_{LR} \Rightarrow \text{no } hZ\gamma$ in the absence of the elementary composite mixing.

- top Yukawa coupling breaks down $P_{LR}$ so these effects will be suppressed by $O \left( \frac{\lambda^2}{M^2_{\ast}} \frac{v^2}{f^2} \right)$, however in the SM top contribution is much smaller than the $W$ contribution.

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

- 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, $A_5 \approx A_{SM} \sqrt{1 - \frac{v^2}{f^2}}$
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

$$\mathcal{L} = m_{4\bar{4}} + m_{(3,1)}(3, 1)^*(3, 1) + m_{(1,3)}(1, 3)^*(1, 3)$$
$$+ 10(\bar{\varphi} - \bar{\xi})10 - \zeta_{13} \bar{\varphi}(1, 3) - \zeta_{31} \bar{\varphi}(3, 1).$$
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

$$\frac{NP_{\text{SM top}}}{NP_{\text{gener}}} |\Delta m \ll m \sim 15 N_{\text{gener}} \times \left( \frac{v}{f} \right)^2 \frac{\Delta m}{m}$$
$P_{LR}$ 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 $\mathbf{5}$ has an accidental $P_{LR}$ (Contino, Rattazzi, Pappadopulo, Marzocca) symmetry due to the fact that

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

$SO(5)/SO(4)$ breaking cannot split masses inside $(2, 2)$
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 $P_{LR}$ model 10 + 5**

<table>
<thead>
<tr>
<th>$q_L$</th>
<th>$-10 - 10 - b_R$</th>
<th>$m_b \sim \lambda_{q}^{10} \lambda_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{q}^{10}$</td>
<td></td>
<td>$\lambda_{q}^{10} \ll \lambda_{q}^{5}$, $Z\bar{b}b$ is fine</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$q_L$</th>
<th>$-5 - 5 - t_R$</th>
<th>$m_t \sim \lambda_{q}^{5} \lambda_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{q}^{5}$</td>
<td></td>
<td></td>
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$L_{mixing} = \lambda_{q}^{10} \bar{q}_L P_q 10 + \lambda_{q}^{5} \bar{q}_L P_q 5 + \lambda_b \bar{b}_R P_b 10 + \lambda_t \bar{t}_R P_t 5$

Forbid mixing between 10 and 5 imposing different $U(1)_X$ charges
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 $\Gamma_{NP}/\Gamma_{SM}$ 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
  \( \text{(Golden, Randall; Barbieri, Isidori, Pappadopulo; Grojean, Matsedonskyi, Panico; AA, Contino, Dillura, Galloway) } \)

\[
\begin{align*}
\mathcal{L} &= \sum_r \bar{\chi}_r (i \gamma^\mu - m_r) \chi_r - \zeta_{rr'} \chi_{r'} \partial \chi_{r'} \\
\Delta S &= -\frac{8\pi}{gg'} \sin^2 \theta \left[ -\Pi'_{3\bar{3}} + \frac{1}{2} \Pi'_{3L3L} + \frac{1}{2} \Pi'_{3R3R} \right] \\
\Delta S &\approx \frac{N_c \sin^2 \theta}{3\pi} \left( 1 - |\zeta|^2 \right) \log \frac{\Lambda^2}{m^2} + \text{finite}
\end{align*}
\]

- $\Delta S$ 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 $O_3^+ = \text{Tr}(E^L_{\mu\nu}E^L_{\mu\nu}) + \text{Tr}(E^R_{\mu\nu}E^R_{\mu\nu})$, 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 $\Delta S$ 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.
We studied $hZ\gamma$ in the Composite Higgs models

$h \rightarrow Z\gamma$ decay receives large new physics corrections that are not suppressed by the Goldstone symmetry arguments.

Contribution of the strong dynamics to the $h \rightarrow Z\gamma$ 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 $h \rightarrow Z\gamma$ decay.

Similar processes lead to the contribution to the $S$ parameter. Negative $\Delta S$ can relax the current EWPT bounds and at the same time accommodate large $h \rightarrow Z\gamma$
hZγ from integrating out ρ

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

$$\mathcal{L} = -\frac{1}{4g_{\rho L}^2} \text{Tr}(\rho^{L}_{\mu\nu}\rho^{L,\mu\nu}) + \frac{m_{\rho L}^2}{2g_{\rho L}^2} \text{Tr}(\rho^{L}_{\mu} - E^{L}_{\mu})^2 + \alpha_{1}^{L} \text{Tr}(\rho^{\mu\nu}_{L} i[d_{\mu} d_{\nu}]) + (L \leftrightarrow R)$$

- Integrating out ρ at tree level we will get

$$c_{Z\gamma} = \frac{g^2}{2} \sin^2 \theta(\alpha_{1}^{L} - \alpha_{1}^{R})$$