$E_6$ inspired composite Higgs model and 750 GeV diphoton excess

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Outline

- Introduction
- $E_6$ inspired composite Higgs model and orbifold GUT
- 750 GeV diphoton resonance
- Conclusions

Based on:


Introduction

- The properties of a new scalar particle, observed by the ATLAS and CMS, strongly suggest that it is the SM–like Higgs boson.
- In the SM the Higgs scalar potential is given by
  \[ V(H) = m_H^2 H^\dagger H + \lambda (H^\dagger H)^2. \]
- The discovery of the BEH boson with \( m_h \approx 125 \text{ GeV} \) allows to estimate the values of parameters
  \[ m_H^2 \approx -(90 \text{ GeV})^2, \quad \lambda \approx 0.13. \]
- In composite Higgs models so small values of \( m_H^2 \) and \( \lambda \) can be obtained if Higgs emerges as a pseudo–Nambu–Goldstone boson (pNGB) from the spontaneous breaking of some global symmetry.
- The composite Higgs models involve weakly–coupled elementary and strongly interacting sectors.
The sector of weakly–coupled elementary particles includes the SM gauge bosons and SM fermions.

The strongly interacting sector results in a set of bound states that involves Higgs doublet as well as composite partners of quarks, leptons and gauge bosons.

At low energies those states identified with SM fermions (bosons) \( (\psi^i_a) \) are a mixture of the corresponding elementary fermionic (bosonic) states \( (\tilde{\psi}^i_a) \) and their fermionic (bosonic) composite partners \( (\tilde{\Psi}^i_a) \), i.e.

\[
|\psi^i_a > = c^i_a |\tilde{\psi}^i_a > + s^i_a |\tilde{\Psi}^i_a >.
\]

The couplings of the SM states to the composite Higgs are determined by the fractions of the compositeness of these states. For up– and down–quarks one gets

\[
y_{ij}^u = s_q Y_{ij}^u s_u,
\]

\[
y_{ij}^d = s_q Y_{ij}^d s_d,
\]

i, j = 1, 2, 3.
The top quark is so heavy that the right–handed top quark ($t^c$) should have sizeable fraction of compositeness.

If $t^c$ is entirely composite then the approximate gauge coupling unification can be achieved [K. Agashe, R. Contino, R. Sundrum, Phys. Rev. Lett. 95 (2005) 171804].

This happens, when all composite states fill in complete $SU(5)$ representations and the set of weakly–coupled elementary states involves

$$(q_i, d_i^c, l_i, e_i^c) + u^c_\alpha + \bar{q} + \bar{d}^c + \bar{l} + \bar{e}^c + \eta, \quad \alpha = 1, 2.$$  

It is expected that the dynamics of the strongly interacting sector leads to the $10 + \bar{5} + 1$ multiplets of $SU(5)$ that get combined with $\bar{q}, \bar{d}^c, \bar{l}, \bar{e}^c$ and $\eta$ forming a set of vector–like states.
The only exceptions are the components of 10–plet associated with $t^c$, which survive down to the EW scale.

In the one–loop approximation the exact gauge coupling unification is attained for $\alpha_3(M_Z) \simeq 0.109$.


Thus it is interesting to consider the embedding of the composite Higgs models into well known GUTs.

In $N = 2$ SUSY GUT based on $E_8$ all SM particles belong to 248 dimensional representation of $E_8$ that decomposes under $E_6$ as follows

$$248 \rightarrow 78 \oplus 3 \times 27 \oplus 3 \times \overline{27} \oplus 8 \times 1.$$
Currently, the best candidate for the "Theory of Everything", i.e. hypothetical single framework that explains and links together all physical aspects of the universe, is ten–dimensional heterotic superstring theory based on $E_8 \times E'_8$.

Within superstring theory gauge and gravitational anomaly cancellation, which is necessary for a consistent theory, was found to occur only for the gauge groups $SO(32)$ or $E_8 \otimes E'_8$.

Compactification of extra dimensions leads to an effective supergravity and results in the breakdown of $E_8$ to $E_6$ or its subgroups in the observable sector.

This stimulates the investigation of the orbifold GUT models based on the $E_6 \otimes G_0$ gauge group.
In the composite Higgs models the appropriate suppression of the baryon number violating operators and the Majorana masses of the left–handed neutrino can be achieved if global $U(1)_B$ and $U(1)_L$ are imposed.

In the $E_6$ inspired models almost exact conservation of the $U(1)_B$ and $U(1)_L$ charges may occur if elementary fermions with different baryon or lepton numbers stem from different 27–plets of $E_6$.

All other components of these 27–plets have to gain masses of the order of $M_X$.

Such a splitting of the $E_6$ fundamental representations can take place within the six–dimensional orbifold SUSY GUT model based on the $E_6 \times G_0$ gauge group.

Near the GUT scale $M_X$ the $E_6 \times G_0$ gauge group is broken down to the $SU(3)_C \times SU(2)_W \times U(1)_Y \times G$. 
Gauge groups $G_0$ and $G$ are associated with the strongly coupled sector.

Fields from the strongly coupled sector can be charged under both $E_6$ and $G_0 (G)$ gauge symmetries.

The weakly–coupled sector involves elementary states that participate in the $E_6$ interactions only.

We consider the compactification of two extra dimensions on the orbifold $T^2/(Z_2 \times Z_2^I \times Z_2^{II})$.

The $Z_2$, $Z_2^I$ and $Z_2^{II}$ reflection symmetries allow to reduce the physical region to a pillow with the four $4D$ branes located at its corners.

In this model the elementary quark and lepton fields are components of different bulk $27$–plets.
The components $\Phi_i$ and $\overline{\Phi}_i$ of the bulk 27 supermultiplet transform under $Z_2$, $Z_2^I$ and $Z_2^{II}$ as follows

\[
\Phi_i(x, -y, -z) = P_{ii} \Phi_i(x, y, z), \quad \overline{\Phi}_i(x, -y, -z) = -P_{ii} \overline{\Phi}_i(x, y, z), \\
\Phi_i(x, -y', -z) = P_{II}^I \Phi_i(x, y', z), \quad \overline{\Phi}_i(x, -y', -z) = -P_{II}^I \overline{\Phi}_i(x, y', z), \\
\Phi_i(x, -y, -z') = P_{II} \Phi_i(x, y, z'), \quad \overline{\Phi}_i(x, -y, -z') = -P_{II} \overline{\Phi}_i(x, y, z'),
\]

where $y' = y - \pi R_5/2$ and $z' = z - \pi R_6/2$.

The elements of $P$, $P^I$ and $P^{II}$ can be written in the following form

\[
(P)_{ii} = \sigma \exp\{2\pi i \Delta \alpha_i\}, \quad (P^I)_{ii} = \sigma_I \exp\{2\pi i \Delta^I \alpha_i\}, \\
(P^{II})_{ii} = \sigma_{II} \exp\{2\pi i \Delta^{II} \alpha_i\},
\]

where $\sigma$, $\sigma_I$ and $\sigma_{II}$ are parities of the bulk 27 supermultiplet, i.e. $\sigma, \sigma_I, \sigma_{II} \in \{+, -\}$; $\alpha_j$ are $E_6$ weights while $\Delta$, $\Delta^I$ and $\Delta^{II}$ are gauge shifts.
We choose the following gauge shifts

\[
\Delta = \left(0, 0, 0, \frac{1}{2}, 0, 0\right), \quad \Delta^I = \left(\frac{1}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}, 0, 0\right), \quad \Delta^{II} = \left(\frac{1}{2}, \frac{1}{2}, \frac{1}{2}, 0, \frac{1}{2}, 0\right),
\]

that correspond to the orbifold parity assignments shown in the Table.

Orbifold parity assignments in the bulk 27\' supermultiplet with

\[
\sigma = \sigma_I = \sigma_{II} = +1.
\]

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On the branes $O$, $O_I$ and $O_{II}$ the $E_6$ gauge group is broken down to $SU(6) \times SU(2)_N$, $SU(6)' \times SU(2)_W$ and $SO(10)' \times U(1)'$ respectively.

All fields from the strongly coupled sector are confined on the brane $O$, where $E_6$ symmetry is broken down to the $SU(6) \times SU(2)_N$ subgroup.

The unbroken gauge group of the effective $4D$ theory is $SU(4)' \times SU(2)_W \times SU(2)_N \times U(1)'$ which is the intersection of the $E_6$ subgroups at the fixed points.

The scalar components of the supremultiplets localised on the branes $O_I$ and $O_{II}$ can be used to break $SU(4)' \times SU(2)_W \times SU(2)_N \times U(1)'$ down to the SM gauge group so that $SU(6)$ symmetry remains intact.

The SM gauge interactions break $SU(6)$ symmetry.
Nonetheless, if the gauge couplings of $G$ are considerably larger than the SM gauge couplings, then $SU(6)$ can be still an approximate global symmetry of the composite sector at low energies.

Thus the strongly interacting sector in the $E_6$ inspired composite Higgs model ($E_6$CHM) possesses $SU(6) \times U(1)_B \times U(1)_L$ global symmetry.

In the $E_6$CHM the lightest exotic fermion state, that do not participate in the SM gauge interactions, may be stable because of the conservation of baryon number/baryon triality

$$\Psi \longrightarrow e^{2\pi i B_3/3} \Psi, \quad B_3 = (3B - n_C) \mod 3,$$

where $n_C$ is the number of colour indices ($n_C = 1$ for the colour triplet and $n_C = -1$ for $\overline{3}$).
Near the scale $f \gtrsim 10\text{ TeV}$ the $SU(6)$ global symmetry is broken down to its $SU(5)$ subgroup, that contains the SM gauge group.

The $SU(6)/SU(5)$ coset space involves eleven pNGB states.

One of these pNGB states $\phi_0$ does not participate in the SM gauge interactions.

Ten others form the SM–like Higgs doublet $H$ and the $SU(3)_C$ triplet $T$.

These pNGB states do not carry any baryon and/or lepton numbers.

Since in the $E_6$ CHM $f \gtrsim 10\text{ TeV}$, a significant tuning, $\sim 0.01\%$, is needed to get the SM–like Higgs with mass $125\text{ GeV}$.
In the E$_6$CHM $\phi_0$ can be identified with the state which results in the excess of diphoton events at an invariant mass around 750 GeV.

It is important that no resonance with mass 750 GeV has been detected in any other channels including $pp \rightarrow t\bar{t}, WW, ZZ, b\bar{b}, \tau\bar{\tau}$ and $jj$.

The state $\phi_0$ could potentially mix with the Higgs boson which would give rise to large partial decay widths of the 750 GeV resonance to $ZZ, WW$ and $t\bar{t}$.

Here invariance under CP transformation is imposed.

In this case $\phi_0$ manifests itself in the Yukawa interactions with fermions as a pseudoscalar field.

Therefore $\phi_0$ can not mix with the Higgs boson because of the almost exact CP–conservation.
The Lagrangian that describes the interactions between $\phi_0 = A$ and other states can be written as

$$\mathcal{L}_A = A (i\kappa_D \bar{d}^c D^c + i\kappa_Q \bar{q}^c Q + i\lambda_L \bar{\ell} L + i\lambda_E \bar{e}^c E^c + i\lambda_\eta \bar{\eta} \eta + \text{h.c.})$$

$$+ \frac{\alpha_Y}{16\pi \Lambda_1} A B_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{\alpha_2}{16\pi \Lambda_2} A W^a_{\mu\nu} \tilde{W}^{a\mu\nu} + \frac{\alpha_3}{16\pi \Lambda_3} A G^\sigma_{\mu\nu} \tilde{G}^{\sigma\mu\nu}$$

$$+ \frac{y_t}{\Lambda_t} A (i\bar{t} L H^0 t_R + \text{h.c.}) + \frac{y_b}{\Lambda_b} A (i\bar{b} L H^0 b_R + \text{h.c.}) + \ldots.$$  

- $\Lambda_1$, $\Lambda_2$ and $\Lambda_3$ are expected to be of the order of scale $f$.
- When $t^c$ belongs to 20 of $SU(6)$, the scale $\Lambda_t = \sqrt{15} f$.
- If $t^c$ belongs to 15 of $SU(6)$ then $\Lambda_t = \sqrt{\frac{60}{49}} f$.

The mass terms of exotic fermions are given by

$$\mathcal{L}_{\text{mass}} = \mu_D \bar{d}^c D^c + \mu_Q \bar{q}^c Q + \mu_L \bar{\ell} L + \mu_E \bar{e}^c E^c + \mu_\eta \bar{\eta} \eta + \text{h.c.}$$

Here we assume that $\mu_D$, $\mu_Q$, $\mu_L$ and $\mu_E$ are larger than 375 GeV.
Integrating out the heavy exotic states one gets

\[ \mathcal{L}_{\text{eff}} = c_1 A B_{\mu\nu} \tilde{B}^{\mu\nu} + c_2 A W_{\mu\nu}^a \tilde{W}^{a\mu\nu} + c_3 A G_{\mu\nu}^\sigma \tilde{G}^{\sigma\mu\nu} + \frac{y_t}{\Lambda_t} A (i \bar{t}_L H t_R + h.c.) + i \lambda_\eta A (\bar{\eta} \eta + h.c.) . \]

The effective Lagrangian that describes the interactions of these fields with the electromagnetic one is given by

\[ \mathcal{L}_{\text{eff}}^{A\gamma\gamma} = c_\gamma A F_{\mu\nu} \tilde{F}^{\mu\nu} , \quad c_\gamma = c_1 \cos^2 \theta_W + c_2 \sin^2 \theta_W . \]

At the LHC the SM singlet pNGB state \( A \) is predominantly produced through gluon fusion.

Then the diphoton production cross section can be approximately estimated as

\[ \sigma_{\gamma\gamma} = \sigma_{gg} \frac{\Gamma(A \to \gamma\gamma)}{\Gamma_A} \simeq 7.3 \text{ fb} \times \left( \frac{\Gamma(A \to gg) \Gamma(A \to \gamma\gamma)}{\Gamma_A m_A} \times 10^6 \right) . \]
If $\mu_\eta > 375 \text{ GeV}$ then the total decay width $\Gamma_A \approx \Gamma(A \to gg)$ tends to be small, $\Gamma_A/m_A \lesssim 10^{-4}$. We focus on the scenario with $\mu_D = \mu_Q = \mu_L = \mu_0 \gtrsim \mu_E$, $\mu_E = 400 \text{ GeV, } 500 \text{ GeV and } 800 \text{ GeV}$ as well as $\kappa_D = \kappa_Q = \lambda_L = \lambda_E = \sigma \approx 1.5$. We also set $\Lambda_t \approx 80 \text{ TeV} (f \approx 20 \text{ TeV})$ to achieve the appropriate suppression of the decay rate $A \to t\bar{t}$. The value of $\mu_0$ should be sufficiently small ($\ll 10 \text{ TeV}$) so that reasonably large LHC production cross section of $A$ can be obtained. The diphoton production cross section decreases rapidly with increasing $\mu_E$. When $\mu_0 \gg \mu_E \approx 400 - 500 \text{ GeV}$ the decay rates for $A \to t\bar{t}, WW, ZZ$ and $Z\gamma$ are rather suppressed that may explain why these decays have not been observed yet.
\sigma(p p \to A \to \gamma\gamma)[fb]

\sigma(p p \to A \to \gamma\gamma)[fb]

\text{BR}(A \to t\bar{t}, gg, \gamma\gamma, WW, ZZ, \gamma Z)

\Gamma_A/m_A
The pseudoscalar $A$ mainly decays into a pair of gluons that might be difficult to detect if the LHC production cross section of $A$ remains rather small.

When $\mu_0 \gg \mu_E$ the branching fraction associated with $A \to \gamma\gamma$ is the second largest one.

$\text{BR}(A \to \gamma\gamma)$ decreases whereas $\text{BR}(A \to ZZ)$ and $\text{BR}(A \to WW)$ increases with decreasing $\mu_0$.

When $\mu_0$ is around 1 TeV the values of $\text{BR}(A \to ZZ)$ and $\text{BR}(A \to WW)$ are a few times bigger than $\text{BR}(A \to \gamma\gamma)$.

Nevertheless the experimental detection of $A \to WW$ and $A \to ZZ$ is more problematic because the $W$ and $Z$ decay mainly into quarks.

In this case $\text{BR}(A \to tt\bar{t})$ and $\text{BR}(A \to \gamma Z)$ are considerably smaller than $\text{BR}(A \to \gamma\gamma)$. 
If $\mu_\eta \lesssim 375 \text{ GeV}$ then the decays of $A$ into $\eta \bar{\eta}$ are kinematically allowed.

As a result $\lambda_\eta$ and $\mu_\eta$ can be always adjusted so that $\Gamma_A \approx 45 \text{ GeV}$ ($\Gamma_A/m_A \approx 0.06$) or even larger.

For so large $\Gamma_A$ the value of $\sigma(pp \rightarrow A \rightarrow \gamma\gamma) \approx 5 - 10 \text{ fb}$ can be obtained only if the masses of all charged exotic fermions are rather close to $375 \text{ GeV}$.

Here we set $\kappa_D = \kappa_Q = \lambda_L = \lambda_E = \sigma$, $\mu_Q = \mu_D$, $\mu_L = \mu_E = 400 \text{ GeV}$ and consider scenarios with $\sigma = \sqrt{4\pi}$ and $\sigma = 2$ for $\Gamma_A = 45 \text{ GeV}$ and $\Gamma_A = 20 \text{ GeV}$.

If $\Gamma_A$ is $20 \text{ GeV}$ or smaller $\sigma(pp \rightarrow A \rightarrow \gamma\gamma) \approx 4 - 5 \text{ fb}$ can be obtained provided the masses of exotic coloured fermions are around $1 \text{ TeV}$ or smaller.
\[ \Gamma(A \to \eta\bar{\eta}) / m_A \]

\[ \sigma(pp \to A \to \gamma\gamma) [fb] \]

\[ \text{BR}(A \to gg, WW, ZZ, \gamma\gamma, \gamma Z, t\bar{t}) \]

\[ \sigma(pp \to A + X) [fb] \]
In general this scenario leads to quite a large cross section of the process $pp \rightarrow j + E_T^{miss}$.

Moreover, the branching ratios of decays $A \rightarrow gg, WW, ZZ$ are considerably larger than the one associated with $A \rightarrow \gamma\gamma$.

The observation of these decay modes should be possible in Run 2 at the LHC.

The exotic coloured fermions with TeV scale masses are doubly produced.

Assuming that such states couple most strongly to the third generation fermions, they decay into a pair of third generation quarks and the lightest neutral exotic state resulting in the enhancement of the cross sections for

$$pp \rightarrow t\bar{t}b\bar{b} + E_T^{miss} + X$$
$$pp \rightarrow b\bar{b}b\bar{b} + E_T^{miss} + X.$$
Conclusions

- In the E\(_6\)CHM the strongly interacting sector possesses an \(SU(6) \times U(1)_B \times U(1)_L\) global symmetry.

- Near scale \(f \gtrsim 10\) TeV the \(SU(6)\) global symmetry is broken down to its \(SU(5)\) subgroup, that contains the SM gauge group, resulting in a set of pNGBs states.

- This set, in particular, involves the SM–like Higgs doublet and a pseudoscalar \(A\).

- The interactions of \(A\) with exotic matter, which ensures anomaly cancellation and approximate gauge coupling unification, induce couplings of \(A\) to gauge bosons.

- As a result, the pseudoscalar \(A\) can be identified with the 750 GeV diphoton resonance.

- Such an interpretation requires that either all or some of the exotic states have masses below 1 TeV.