Composite models for 750 GeV diphoton excess at the LHC

Chaehyun Yu

Collaboration with P. Ko (KIAS), T.C. Yuan (AS)
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Diphoton excess

• Resonance in the $\gamma\gamma$ mode at 750 GeV

• Local significance = 3.9$\sigma$ (ATLAS), 3.4$\sigma$ (CMS), but LEE significantly reduce the significance $\sim 2\sigma$

• spin=0 or spin=2,
  spin=1 may be OK (with cascade decays, ex. photon jets)

• $\Gamma/M \sim 0.06$ (ATLAS), $10^{-2}$~$10^{-4}$ (CMS) preferred

• Cross section = $10\pm3$ fb (ATLAS), 2~6 fb (CMS)
CMS Run I + Run II

less preferred

largest excess in 13 TeV data
local 2.8~2.9$\sigma$

largest excess in combined
local 3.4$\sigma$
Composite models

• a new confining gauge force described by gauge group SU($N_h$)

• a new vector-like $h$-quark (hyper quark) $Q$ or scalar quark $\tilde{Q}$

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(N_h) : (3,1,Y,N_h)$$

free parameter, set $Y$ to be $+2/3$

• the confinement scale $\Lambda_h$

$$\Lambda_h \approx M \exp \left[ -\frac{6\pi}{(11N_h - 2n_f)\alpha_h(M)} \right]$$

• both $Q$ and $\tilde{Q}$ are heavier than the confinement scale $\Lambda_h$.

• Simply assume that $Q$ is the only hyper-quark or the lightest one.

• $h$-gluons evolve into $h$-glueballs which eventually decay into SM particles through Q loop
Potential of bound state

• Coulomb dominance may be a reasonably good approximation for the entire range of $\alpha_h$.

• Assume the Coulomb potential

\[ V = -\frac{C_h \alpha_h}{r} - \frac{C_F \alpha_s}{r} \]
Wavefunction at the origin

**Coulomb**

\[ V(r) = -\frac{4}{3} \frac{\alpha_s(m_Q^2)}{r} \]

**Cornell**

\[ V(r) = -k/r + ar \]

**Richardson**

\[ V(Q) = -\frac{4}{3} \frac{12\pi}{33 - 2N_f} \frac{1}{Q^2 \ln(1 + Q^2/\Lambda^2)} \]

**Wisconsin**

\[ V(r) = V_5(r) + V_1(r) + ar \]

\[ V_5(r) = -\frac{4\alpha_s(r)}{3r} \]

\[ V_1(r) = r(c_1 + c_2r)e^{-r/r_0} \]

Barger et al., PRD35, 3366
Glueball mass in pure SU(3)

quenched lattice calculation

unquenched lattice calculation

Chen et al., PRD73, 014516

Glueball has not been detected and the mass prediction might have uncertainties

\[ M_G \approx (4 \sim 7) \times \Lambda \]
Glueball mass in pure SU(3)

$M_G = 5 \sim 500 \text{ GeV}$
SU(2) singlet fermion model

- fix $m_Q = 375$ GeV for interpreting the diphoton excess as a bound state of $Q\bar{Q}$ in the spin-singlet S-wave state, $\eta_Q$.

- the binding energy is

$$M(n^{2S+1}L_J) \approx 2m_Q \left[ 1 - \frac{C_h^2 \alpha_h^2}{8n^2} \right]$$

- the mass of the excited state is

$$M(\eta_Q') = 750 \text{GeV} \left( \frac{1 - C_h^2 \alpha_h^2/32}{1 - C_h^2 \alpha_h^2/8} \right)$$

- the spin-triplet partner, $\psi_Q$

$$\Delta M \equiv M_{\psi_Q} - M_{\eta_Q} = M_{\eta_Q} \frac{16\pi}{3} \alpha_h \frac{|R_S(0)|^2}{M^3} \approx M_{\eta_Q} \frac{\pi}{3n^2} (C_h \alpha_h)^4$$

$$\Delta M \lesssim (4, 13, 35) \text{ GeV for } N_h = (3, 4, 5)$$
Decays into $WW$ or $ff$ are forbidden due to SU(2) singlet nature

Eventually $h$-gluons would evolve into $h$-glueballs if kinematically allowed

If there exist lighter $h$-quarks, $\eta_Q$ can decay into the bound states made of the light $h$-quarks.
Branching ratios

\[ \eta_Q \rightarrow g_h g_h \]

\[ \eta_Q \rightarrow g_h g_h \]

\[ \eta_Q \rightarrow g_h g_h \]

\[ \eta_Q \rightarrow g_h g_h \]
The production cross section $\propto$ the wavefunction at the origin
Diphoton cross section

\[ \eta_Q \rightarrow g_h g_h \]

\[ \eta_Q \rightarrow g_h g_h \]

\[ \sigma(pp\rightarrow \eta_Q\rightarrow \gamma\gamma) \text{ [fb]} \]

\[ \Gamma_{\text{tot}} \text{ [GeV]} \]

\[ \text{ATLAS Run-II} \]

\[ \text{CMS Run-II} \]

\[ \text{CMS combined} \]
Spin-triplet partner $\Psi_Q$

\[
\Gamma(\psi_Q \rightarrow g_h g_h g_h) = \frac{(\pi^2 - 9)\alpha_s^3}{36\pi m_Q^2} \frac{N_c (N_h^2 - 1)(N_h^2 - 4)}{N_h^2} |R_{1S}(0)|^2
\]

\[
\Gamma(\psi_Q \rightarrow ggg) = \frac{(\pi^2 - 9)\alpha_s^3}{36\pi m_Q^2} \frac{N_h (N_c^2 - 1)(N_c^2 - 4)}{N_c^2} |R_{1S}(0)|^2
\]

might be forbidden kinematically

$\psi_Q$ can decay into a pair of fermions via $\gamma$ or $Z$ exchanges

\[
\Gamma(\psi_Q \rightarrow l^+l^-) = \frac{N_c N_h \alpha_s^2 e_Q^2}{3m_Q^2} \left[ 1 - \frac{2(1 - 4x_w)}{(4 - r_Z)(1 - x_w)} + \frac{2(1 - 4x_w + 8x_w^2)}{(4 - r_Z)^2(1 - x_w)^2} \right] |R_{1S}(0)|^2
\]

$\psi_Q$ does not decay into $\gamma\gamma$, $\gamma Z$, $ZZ$ due to SU(2) singlet nature, but it can decay into $WW$ through small SU(2) breaking terms

\[
\Gamma(\psi_Q \rightarrow \gamma gg) = \frac{(\pi^2 - 9)\alpha_s^2 e_Q^2}{3\pi m_Q^2} \frac{N_h (N_c^2 - 1)}{N_c} |R_{1S}(0)|^2
\]

\[
\Gamma(\psi_Q \rightarrow \gamma g_h g_h) = \frac{(\pi^2 - 9)\alpha_s^2 e_Q^2}{3\pi m_Q^2} \frac{N_c (N_h^2 - 1)}{N_h} |R_{1S}(0)|^2
\]

g_h g_h evolves into a $h$-glueball if kinematically allowed
Spin-triplet partner $\Psi_Q$

$\Psi_Q \rightarrow g_h g_h g_h$

Graphs showing branching ratios for different $N_h$ values.
Production cross section of $\psi_Q$

**Drell-Yan**

\[
\sigma_{DY}(q\bar{q} \rightarrow \psi_Q \rightarrow l^+l^-) = \frac{(2J_{\psi_Q} + 1)\Gamma(\psi_Q \rightarrow l^+l^-)}{sm_{\psi_Q} \Gamma_{\psi_Q}} \sum_{q\bar{q}} C_{q\bar{q}} \Gamma(\psi_Q \rightarrow q\bar{q})
\]

**hadro-production**

\[
C_{q\bar{q}} = \frac{4\pi^2}{9} \int_{M^2/s}^{1} \frac{dx}{x} \left[q(x)\bar{q}(\frac{M^2}{sx}) + \bar{q}(x)q(\frac{M^2}{sx})\right]
\]

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>$C_{bb}$</th>
<th>$C_{cc}$</th>
<th>$C_{ss}$</th>
<th>$C_{d\bar{d}}$</th>
<th>$C_{u\bar{u}}$</th>
<th>$C_{g\bar{g}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 TeV</td>
<td>1.07</td>
<td>2.7</td>
<td>7.2</td>
<td>89</td>
<td>158</td>
<td>174</td>
</tr>
<tr>
<td>13 TeV</td>
<td>15.3</td>
<td>36</td>
<td>83</td>
<td>627</td>
<td>1054</td>
<td>2137</td>
</tr>
</tbody>
</table>
Drell-Yan production

\[ \psi_Q \rightarrow g_h g_h g_h \]

\[ \psi_Q \rightarrow g_h g_h g_h \]

Graphs showing the cross-sections for Drell-Yan production at different center-of-mass energies and for different numbers of gluons in the final state.
SU(2) singlet scalar model

- fix $m_Q=375$ GeV for interpreting the diphoton excess as a bound state of $\tilde{Q}\tilde{Q}$ in the hypercolor-singlet S-wave state, $\eta_{\tilde{Q}}$.

- no spin-triplet partner since the constituent particles are scalar quarks

- $J^{PC}=1^{--}$ state comes from radial excitation with nonzero orbital angular momentum, $J=L=1$.

\[
\begin{align*}
\Gamma(\eta_{\tilde{Q}} \rightarrow \gamma\gamma) &= \frac{N_cN_h\alpha^2e_\gamma^2}{2m_{\tilde{Q}}^2}\left|\tilde{R}_{1S}(0)\right|^2 \\
\Gamma(\eta_{\tilde{Q}} \rightarrow \gamma Z) &= \frac{N_cN_h\alpha^2e_\gamma^2m_{\eta_{\tilde{Q}}}}{4m_{\tilde{Q}}^2(1-x_w)}\left|\tilde{R}_{1S}(0)\right|^2 \\
\Gamma(\eta_{\tilde{Q}} \rightarrow gg) &= \frac{N_h(N_c^2-1)\alpha^2}{8N_c^2m_{\tilde{Q}}^2}\left|\tilde{R}_{1S}(0)\right|^2 \\
\Gamma(\eta_{\tilde{Q}} \rightarrow ZZ) &= \frac{N_cN_h\alpha^2e_\gamma^2m_{\eta_{\tilde{Q}}}}{4m_{\tilde{Q}}^2(2-r_Z)^2(1-x_w)^2}\left|\tilde{R}_{1S}(0)\right|^2 \\
\Gamma(\eta_{\tilde{Q}} \rightarrow g_h\bar{g}_h) &= \frac{N_c(N_h^2-1)\alpha^2_h}{8N_h^2m_{\tilde{Q}}^2}\left|\tilde{R}_{1S}(0)\right|^2
\end{align*}
\]

Eventually h-gluons would evolve into h-glueballs.
SU(2) singlet scalar model

\( \eta_0 \rightarrow g_h g_h \)

\( \eta_0 \rightarrow g g_h \)
SU(2) singlet scalar model

\( \eta_0 \rightarrow g_h g_h \)

\( \eta_0 \rightarrow g_h g_h \)
\[\Gamma(\chi \bar{Q} \rightarrow uu) = \frac{N_c^2 N_h \alpha_s^2 e_Q^2}{9 m_Q^4} \left[ 2 - \frac{2(3 - 8x_w)}{(4 - r_Z)(1 - x_w)} + \frac{9 - 24x_w + 32x_w^2}{(4 - r_Z)^2(1 - x_w)^2} \right] |R'_{2P}(0)|^2 \]

\[\Gamma(\chi \bar{Q} \rightarrow dd) = \frac{N_c^2 N_h \alpha_s^2 e_Q^2}{18 m_Q^4} \left[ 1 - \frac{2(3 - 4x_w)}{(4 - r_Z)(1 - x_w)} + \frac{2(9 - 12x_w + 8x_w^2)}{(4 - r_Z)^2(1 - x_w)^2} \right] |R'_{2P}(0)|^2 \]

\[\Gamma(\chi \bar{Q} \rightarrow t^+ t^-) = \frac{N_c^2 N_h \alpha_s^2 e_Q^2}{2m_Q^4} \left[ 1 - \frac{2(1 - 4x_w)}{(4 - r_Z)(1 - x_w)} + \frac{2(1 - 4x_w + 8x_w^2)}{(4 - r_Z)^2(1 - x_w)^2} \right] |R'_{2P}(0)|^2 \]

\[\Gamma(\chi \bar{Q} \rightarrow \nu \bar{\nu}) = \frac{N_c^2 N_h \alpha_s^2 e_Q^2}{m_Q^4(4 - r_Z)^2(1 - x_w)^2} |R'_{2P}(0)|^2 \]

\[\Gamma(\tilde{\chi} Q \rightarrow ggg) = \frac{(N_c^2 - 1)(N_c^2 - 4) N_h}{N_c} \alpha_s^3 \log \frac{m_Q}{\Delta} |R'_{2P}(0)|^2 \]

\[\Gamma(\tilde{\chi} Q \rightarrow g_h g_h g_h) = \frac{(N_h^2 - 1)(N_h^2 - 4) N_h}{N_h} \alpha_s^3 \log \frac{m_Q}{\Delta} |R'_{2P}(0)|^2 \]

\[\Gamma(\tilde{\chi} Q \rightarrow \gamma gg) = \frac{(N_c^2 - 1) N_h \alpha_s^2 \alpha e_Q^2}{48 m_Q^4} \log \frac{m_Q}{\Delta} |R'_{2P}(0)|^2 \]

\[\Gamma(\tilde{\chi} Q \rightarrow \gamma g_h g_h) = \frac{(N_h^2 - 1) N_c \alpha_s^2 \alpha e_Q^2}{48 m_Q^4} \log \frac{m_Q}{\Delta} |R'_{2P}(0)|^2 \]

IR divergent

\[\Delta = \text{IR regulator}\]
P-wave state $\chi_{\tilde{Q}}$

$\chi_{\tilde{Q}} \rightarrow g_h g_h g_h$

$\chi_{\tilde{Q}} \not\rightarrow g_h g_h g_h$
Drell-Yan production

\[ \chi_Q \rightarrow g_h g_h g_h \]

\[ \chi_Q \rightarrow g_h g_h g_h \]
Color-octet bound state

- h-color-singlet but QCD-color-octet bound state

\[ V = -\frac{C_h \alpha_h}{r} + \frac{C_8 \alpha_s}{r} \]

- \( \eta_Q^8 \) can decay into gg, g\( \gamma \), gZ

\[ \Gamma[\eta_Q^8 \rightarrow gg] = \frac{(N_c^2 - 1)(N_c^2 - 4)N_h \alpha_s^2}{8 N_c m_Q^2} \left| R_{\eta_Q}(0) \right|^2 \]

\[ \Gamma[\eta_Q^8 \rightarrow g\gamma] = \frac{(N_c^2 - 1)N_h \alpha_s \alpha_s Q^2}{m_Q^2} \left| R_{\eta_Q}(0) \right|^2 \]

- constrained by dijet search and photon+jet search
Color-octet bound state

\( \eta_Q \leftrightarrow g_h g_h \)

\( \eta_Q \rightarrow g_h g_h \)

- Assuming (acceptance×efficiency) ~ 0.33 for the photon+jet search
$\eta_Q \rightarrow g_h g_h$

$N_h = 3$

$N_h = 4$

$N_h = 5$

$\Gamma / M = 1.4 \times 10^{-2}$
Fermionic quark

\[ \eta_Q \leftrightarrow g_h g_h \]

\[ N_h = 3 \quad N_h = 4 \quad N_h = 5 \]

\[ \frac{\Gamma}{M} = 1.4 \times 10^{-4} \quad \frac{\Gamma}{M} = 1.4 \times 10^{-3} \]
Scalar quark

$\eta_Q \to g_h g_h$

$N_h = 3$

$N_h = 4$

$N_h = 5$
Scalar quark

\[ \eta_Q \leftrightarrow g_h g_h \]

$N_h = 3$   $N_h = 4$   $N_h = 5$
Conclusions

• We consider a possibility that the diphoton excess is a composite (pseudo)scalar boson made of $Qar{Q}$ or $\tilde{Q}\tilde{Q}^\dagger$.

• The composite models predict the spin-triplet partner and higher-resonant states, which will be observed soon at the LHC.

• The photon+jet search gives the most stringent bound to the composite models with new strong interactions.

• need more data to conclude….
Typical $\Gamma/M$ in QCD

Large $\Gamma/M$ might be achieved in the composite model with QCD-like interactions, but requires a large coupling.
The 750 GeV resonance cannot decay into glueballs.
ATLAS: local 3.6\(\sigma\) (global 2.0\(\sigma\))
\(\sigma(pp\rightarrow\gamma\gamma) \sim 10\) fb with \(\Gamma \sim 45\) GeV

CMS: local 2.6\(\sigma\) for narrow width <2\(\sigma\) for wide width (global <1.2\(\sigma\))

ATLAS data prefer large width \(\Gamma/M \sim 0.06\) while CMS data prefer narrow width
SU(2) doublet fermionic model

\[ \eta_Q \rightarrow g_h g_h \]

\[ \psi_Q \rightarrow g_h g_h g_h \]
How to distinguish models?

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>$\eta_0$</th>
<th>$\eta_0^*$</th>
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<tbody>
<tr>
<td>$0^{-+}$</td>
<td>$0^{++}$</td>
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- The polarization of two photons in the final state should be orthogonal vs. parallel.
- The azimuthal angle distribution of the forward dijet in $gg \rightarrow \eta_Q (\text{or } \eta_{\bar{Q}}) \rightarrow \gamma \gamma$.
- The angular distribution of decay products of Z bosons in $gg \rightarrow \eta_Q (\text{or } \eta_{\bar{Q}}) \rightarrow ZZ$.
- The Drell-Yan production of the spin-triplet partners, etc.