750 GeV diphoton excess in unified left-right symmetric models from NCG

Chen Sun

May 10, 2016

With Ufuk Aydemir, Djordje Minic, Tatsu Takeuchi, arXiv:1603.01756
Quick overview of the LHC excess

\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)

\( m_{X} \) [GeV]

\begin{align*}
\text{Events / 40 GeV} & \quad 10^4 \quad 10^3 \quad 10^2 \quad 10 \quad 1 \quad 10^{-1} \quad 10^{-2} \\
\text{Data - fitted background} & \quad 15 \quad 10 \quad 5 \quad 0 \quad -5 \quad -10 \quad -15 \\
\end{align*}

\( m_{\gamma\gamma} \) [GeV]

\begin{align*}
\text{Local p-value} & \quad 10^{-5} \quad 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 1 \\
\end{align*}

\( 95\% \text{ CL Upper Limit on } \sigma \times \text{BR} \) [fb]

\begin{align*}
\text{Observed} & \quad \text{Expected} \\
\end{align*}
Quick overview of the LHC excess

\[ \bar{\kappa} = 0.1 \]

Observed \( p^+ (13 \text{ TeV}) \)

\(-1.26 \text{ fb} \)

CMS Preliminary

\[ \sigma = 0.1 \]

\( \kappa \sim 0 \)

\( 750 \text{ GeV through NCG} \)

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Quick overview of the LHC excess

The recent diphoton excess:

\[ gg \rightarrow \gamma\gamma \]

<table>
<thead>
<tr>
<th></th>
<th>Local Significance</th>
<th>Data ( @ 13 \text{ TeV} )</th>
<th>XSec Upper Limit (95% CL)</th>
<th>Preferred Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>3.6( \sigma )</td>
<td>3.2 fb(^{-1})</td>
<td>10 ( \pm ) 2.8 fb</td>
<td>(~ 45 \text{ GeV} )</td>
</tr>
<tr>
<td>CMS</td>
<td>2.6( \sigma )</td>
<td>2.6 fb(^{-1})</td>
<td>6.5 ( \pm ) 3.5 fb</td>
<td>Narrow</td>
</tr>
</tbody>
</table>

Highlights:

- The anomaly is seen in both ATLAS and CMS.
- Combining Run I and Run II increases the statistical significance.
- Hard to conclude whether it is narrow or wide at the moment.
- A spin-0 resonance is favored over spin-2. Parity not determined yet.

The Effective Vertices
- $S$ is a Standard Model singlet.
- $\chi$ is a scalar with EM charge and color.
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The effective coupling is $\sim \kappa M_S \chi^\dagger \chi$. 
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- Collider analysis shows LHC signal can be reproduced for $\kappa \sim O(1)$, $M \sim O(1 \text{ TeV})$ and $M_\chi \sim O(1 \text{ TeV})$.

(c.f. Aydemir and Mandal 2016)
The Effective Vertices

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(c.f. Aydemir and Mandal 2016)

- **Upshot:** Unified Pati-Salam through NCG provides $S$ and $\chi$. 
Gauge group $SU(4)_C \times SU(2)_L \times SU(2)_R$. 
- Gauge group $SU(4)_C \times SU(2)_L \times SU(2)_R$.

- $SU(3) \times SU(2)_L \times U(1) \subset SU(3) \times SU(2)_L \times SU(2)_R \times U(1) \subset SU(4) \times SU(2) \times SU(2)$. 
Gauge group $SU(4)_C \times SU(2)_L \times SU(2)_R$.

$SU(3) \times SU(2)_L \times U(1) \subset SU(3) \times SU(2)_L \times SU(2)_R \times U(1) \subset SU(4) \times SU(2) \times SU(2)$.

- Left right symmetric, but still with three couplings (as opposed to the case of GUTs), and the Higgs content undetermined.
$SU(4) \times SU(2)_L \times SU(2)_R \rightarrow SU(3) \times SU(2)_L \times U(1)_Y$

$(4, 2, 1) \rightarrow (3, 2)_{\frac{1}{6}} \oplus (1, 2)_{-\frac{1}{2}}$,

$(\bar{4}, 1, 2) \rightarrow (\bar{3}, 1)_{\frac{1}{3}} \oplus (\bar{3}, 1)_{-\frac{2}{3}} \oplus (1, 1)_1 \oplus (1, 1)_0$,

$(6, 1, 1) \rightarrow (3, 1)_{-\frac{1}{3}} \oplus (\bar{3}, 1)_{\frac{1}{3}}$,

$(1, 3, 1) \rightarrow (1, 3)_0$,

$(1, 1, 3) \rightarrow (1, 1)_1 \oplus (1, 1)_0 \oplus (1, 1)_{-1}$. 
$SU(4) \times SU(2)_L \times SU(2)_R \rightarrow SU(3) \times SU(2)_L \times U(1)_Y$

$(4, 2, 1) \rightarrow (3, 2)^{\frac{1}{6}} \oplus (1, 2)^{-\frac{1}{2}},$

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$(6, 1, 1) \rightarrow (3, 1)^{\frac{1}{3}} \oplus (\bar{3}, 1)^{\frac{1}{3}},$

$(1, 3, 1) \rightarrow (1, 3)_0,$

$(1, 1, 3) \rightarrow (1, 1)_1 \oplus (1, 1)_0 \oplus (1, 1)_{-1}.$

With arbitrariness in Higgs content and coupling relations, we focus on a specific class of Pati-Salam models that are predicted by noncommutative geometry.
Noncommutative geometry was
- mainly developed by Alain Connes in 1980’ (cyclic cohomology),
- and applied to particle physics in early 1990’.
- Includes neutrino mass in 2006.
Quick Facts from NCG:

- $\phi \rightarrow D$

\[
\overline{\psi} \phi \psi + m \overline{\psi} \psi \rightarrow \left[ \overline{\psi}_R \quad \overline{\psi}_L \right] \left[ \begin{array}{cc} \phi & m \\ m & \phi \end{array} \right] \left[ \begin{array}{c} \psi_R \\ \psi_L \end{array} \right]
\]
Quick Facts from NCG:

- $\partial \rightarrow D$

\[
\bar{\psi} \partial \psi + m \bar{\psi} \psi \rightarrow \begin{bmatrix} \bar{\psi}_R & \bar{\psi}_L \end{bmatrix} \begin{bmatrix} \partial & m \\ m & \partial \end{bmatrix} \begin{bmatrix} \psi_R \\ \psi_L \end{bmatrix}
\]

- Make it gauge invariant.

$\partial$ generates the ordinary gauge field $W_\mu^\pm / Z_\mu / A_\mu$.

$\begin{bmatrix} m & m \\ m & m \end{bmatrix}$ generates the discrete gauge field $\phi$. 
Quick Facts from NCG:

- \( \partial \to D \)

\[
\overline{\psi} \partial \psi + m \overline{\psi} \psi \to \begin{bmatrix} \overline{\psi}_R & \overline{\psi}_L \end{bmatrix} \begin{bmatrix} \partial & m \\ m & \partial \end{bmatrix} \begin{bmatrix} \psi_R \\ \psi_L \end{bmatrix}
\]

- Make it gauge invariant.

- \( \partial \) generates the ordinary gauge field \( W^\pm_\mu/ Z_\mu/ A_\mu \).

- \[
\begin{bmatrix} m \\ m \end{bmatrix}
\]
generates the discrete gauge field \( \phi \).

- Two sheet picture: left and right, with mass matrix being the discrete derivative connecting the two.
Quick Facts from NCG:

- $\partial \rightarrow D$

\[
\bar{\psi} \partial \psi + m \bar{\psi} \psi \rightarrow \begin{bmatrix} \bar{\psi}_R & \bar{\psi}_L \end{bmatrix} \begin{bmatrix} \phi & m \\ m & \phi \end{bmatrix} \begin{bmatrix} \psi_R \\ \psi_L \end{bmatrix}
\]

- Make it gauge invariant.

$\partial$ generates the ordinary gauge field $W_\mu^\pm/Z_\mu/A_\mu$.

$\begin{bmatrix} m \\ m \end{bmatrix}$ generates the Higgs field $\phi$.

- Two sheet picture: left and right, with mass matrix being the discrete derivative connecting the two.
What is this construction good for?
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Among the conclusions from NCG:

- Gauge coupling unification:
  \[ g^2 F^2 = g_R^2 W_{\mu\nu} W^{\mu\nu} + g_L^2 F_{\mu\nu} F^{\mu\nu} + g_4^2 G_{\mu\nu} G^{\mu\nu}, \]
  with \( g_L^2 = g_R^2 = g_4^2 \equiv g^2 \) at \( M_U \).

- Restricted Higgs content. (c.f. Chamseddine et. al. 2015)
<table>
<thead>
<tr>
<th>Model</th>
<th>Symmetry</th>
<th>Higgs Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$G_{224}$</td>
<td>$\phi(2, 2, 1), \tilde{\Delta}_R(1, 2, 4), \Sigma(1, 1, 15)$</td>
</tr>
<tr>
<td>B</td>
<td>$G_{224}$</td>
<td>$\phi(2, 2, 1), H(1, 1, 6), \Delta_R(1, 3, 10), \tilde{\Sigma}(2, 2, 15)$</td>
</tr>
<tr>
<td>C</td>
<td>$G_{224D}$</td>
<td>$\phi(2, 2, 1), H(1, 1, 6) \times 2, \Delta_R(1, 3, 10), \Delta_L(3, 1, 10)$, $\tilde{\Sigma}(2, 2, 15)$</td>
</tr>
<tr>
<td>( G_{224} )</td>
<td>( G_{2213} )</td>
<td>( G_{213} )</td>
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</tr>
<tr>
<td>( \phi(2, 2, 1) )</td>
<td>( \phi(2, 2, 0, 1) )</td>
<td>( \phi_2(2, 1, 1), \phi'_2(2, -1, 1) )</td>
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<td>( \tilde{\Delta}_R(1, 2, 4) )</td>
<td>( \tilde{\Delta}_R(1, 2, 1, 1) )</td>
<td>( \tilde{\Delta}^0 R_1(1, 0, 1), \tilde{\Delta}^+_R(1, 2, 1) )</td>
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<td>( \tilde{\Delta}_R(1, 2, 1, 1) )</td>
<td>( \tilde{\Delta}_{1/3} R_3(1, 2, -\frac{1}{3}, 3), \tilde{\Delta}^{-2/3} R_3(1, -\frac{4}{3}, 3) )</td>
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<td>( \Delta_R(1, 3, 10) )</td>
<td>( \Delta_R(1, 3, 2, 1) )</td>
<td>( \Delta^0 R_1(1, 0, 1), \Delta^+_R(1, 2, 1), \Delta^{++}_R(1, 4, 1) )</td>
</tr>
<tr>
<td>( \Delta_{R_3}(1, 3, \frac{2}{3}, 3) )</td>
<td>( \Delta^{+4/3}_R(1, \frac{8}{3}, 3), \Delta^{+1/3}_R(1, \frac{2}{3}, 3), \Delta^{-2/3}_R(1, -\frac{4}{3}, 3) )</td>
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<td>( \Delta_{R_6}(1, 3, -\frac{2}{3}, 6) )</td>
<td>( \Delta^{+2/3}_R(1, \frac{4}{3}, 6), \Delta^{-1/3}_R(1, -\frac{2}{3}, 6), \Delta^{-4/3}_R(1, -\frac{8}{3}, 6) )</td>
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<td>( \Delta_L(3, 1, 10) )</td>
<td>( \Delta_L(3, 1, 2, 1) )</td>
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<td>$H_3^{1/3}\left(1, \frac{2}{3}, 3\right)$</td>
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<td>---------------------</td>
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<td></td>
<td>$H_3\left(1, 1, -\frac{2}{3}, \bar{3}\right)$</td>
<td>$H_3^{-1/3}\left(1, -\frac{2}{3}, \bar{3}\right)$</td>
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<tr>
<td>$\Sigma(1,1,15)$</td>
<td>$\Sigma_1(1,1,0,1)$</td>
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<td>$\Sigma_8(1,1,0,8)$</td>
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<td>$\tilde{\Sigma}(2,2,15)$</td>
<td>$\tilde{\Sigma}_1(2,2,0,1)$</td>
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<td>$\tilde{\Sigma}_3\left(2, -\frac{7}{3}, 3\right), \tilde{\Sigma}_3^\prime\left(2, -\frac{1}{3}, 3\right)$</td>
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</table>
### Identification of $\mathcal{S}$ and $\chi$ – Cont’d

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<tr>
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<th>$H(1,1,6)$</th>
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</table>
\[ M_U \geq M_C \geq M_Z. \]

We label the energy intervals in between symmetry breaking scales \([M_Z, M_C]\) and \([M_C, M_U]\) with Roman numerals as

I : \([M_Z, M_C]\), \(G_{213} (\text{SM})\),

II : \([M_C, M_U]\), \(G_{224}\) or \(G_{224D}\).

Identify \(S\) with \(\tilde{\Delta}^0_{R1}(1, 0, 1)\) or \(\Delta^0_{R1}(1, 0, 1)\), with \(m_S = 750\) GeV.

Identify \(\chi\) with \(\tilde{\Delta}_{R3}^{-2/3}\left(1, -\frac{4}{3}, 3\right)\), with \(m_\chi \sim 1\) TeV.
\[ M_U \geq M_C \geq M_Z. \]

We label the energy intervals in between symmetry breaking scales \([M_Z, M_C]\) and \([M_C, M_U]\) with Roman numerals as

\[
\begin{align*}
\text{I} & : \ [M_Z, M_C], \quad G_{213} \ (\text{SM}), \\
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\end{align*}
\]

Identify \(S\) with \(\Delta^0_{R1}(1, 0, 1)\) or \(\Delta^0_{R1}(1, 0, 1)\), with \(m_S = 750 \text{ GeV}\).

Identify \(\chi\) with \(\Delta^{-2/3}_{R3}(1, -\frac{4}{3}, 3)\), with \(m_\chi \sim 1 \text{ TeV}\).

- Simplicity.
- Including more intermediate scales do not help.

(c.f. 1509.01606, 1512.00568)
\[ M_U : \quad g_L(M_U) = g_R(M_U) = g_4(M_U), \]
\[ M_C : \quad \sqrt{\frac{2}{3}} g_{BL}(M_C) = g_3(M_C) = g_4(M_C), \quad g_2(M_C) = g_L(M_C), \]
\[ \frac{1}{g_1^2(M_C)} = \frac{1}{g_1^2(M_C)} + \frac{2}{3} \frac{1}{g_4^2(M_C)}, \]
\[ M_Z : \quad \frac{1}{e^2(M_Z)} = \frac{1}{g_1^2(M_Z)} + \frac{1}{g_2^2(M_Z)}. \]
\[ \alpha(M_Z) = 1/127.9, \quad \alpha_s(M_Z) = 0.118, \quad \sin^2 \theta_W(M_Z) = 0.2312, \]

at \( M_Z = 91.1876 \text{ GeV} \), which translates to

\[ g_1(M_Z) = 0.36, \quad g_2(M_Z) = 0.65, \quad g_3(M_Z) = 1.22. \]
Requirements

- $M_U \geq M_C \geq M_Z$ is always maintained.
- $M_{Pl} > M_U$.
- Couplings remain perturbative.

$S$ does not contribute to RG running of SM gauge couplings because it is a SM singlet.
## The results

<table>
<thead>
<tr>
<th>Model</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unbroken Symmetry</td>
<td>$G_{224}$</td>
<td>$G_{224}$</td>
<td>$G_{224D}$</td>
</tr>
<tr>
<td>$\log_{10}(M_U/\text{GeV})$</td>
<td>15.7</td>
<td>17.1</td>
<td>15.6</td>
</tr>
<tr>
<td>$\log_{10}(M_C/\text{GeV})$</td>
<td>13.3</td>
<td>10.5</td>
<td>13.4</td>
</tr>
<tr>
<td>$\alpha^{-1}_U$</td>
<td>45.4</td>
<td>34.7</td>
<td>36.2</td>
</tr>
</tbody>
</table>
The results – Cont’d

Model A

Model B

Model C

\[ \alpha^{-1}[\mu] = 4\pi g^2[\mu] \]

\[ \log_{10}[\mu/\text{GeV}] \]

\[ \alpha^{-1}_1, \alpha^{-1}_{2, L}, \alpha^{-1}_R, \alpha^{-1}_{3, 4} \]
Given the fact that

\[ M_C \sim 10^{10} \text{GeV} - 10^{13} \text{GeV}, \]

while the effective coupling \( \sim \kappa M S \chi^\dagger \chi \) has to be very small to produce the observed excess.

Recall

\( \kappa \sim O(1) \) only when \( M \sim O(1 \text{TeV}) \), to reproduce the desired excess.

Fine tuning thus appears.
Given the fact that

\[ M_C \sim 10^{10} \text{GeV} - 10^{13} \text{GeV}, \]

while the effective coupling \( \sim \kappa M S \chi^\dagger \chi \) has to be very small to produce the observed excess. Fine tuning thus appears.

On the other hand, all these analysis is based on EFT, while NCG is not an EFT for sure. The conjectures are

- UV/IR,
- Above some scale, the running of coupling is determined by the geometry, instead of EFT loop diagram correction.

The right interpretation should be, the rigidity from phenomenological side may be the price one has to pay to fit a non-EFT/ nonlocal theory into EFT, and could be a hint for the unique nature of NCG approach.
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Conclusions

- NCG does provide working examples that can explain the diphoton excess.
- The NCG features we have used in this paper are the restricted Higgs content and gauge coupling unification.
- There are other features NCG provides, including mass relations and self couplings for Higgs potentials. We need to study the consequences and phenomenological constraints on that.

It requires some amount of fine tuning. But given people's knowledge of NCG, we should interpret this as some hint for non-ordinary and perhaps unique features NCG provides.
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Thank you!
\[ \tilde{\Delta}_R(1, 2, 4) = \tilde{\Delta}^0_{R1}(1, 0, 1) + \tilde{\Delta}^{-2/3}_{R3}(1, -\frac{4}{3}, 3) + ... \]

\[ (\tilde{\Delta}_R)^4 \sim \]

\[ (\tilde{\Delta}^0_{R1} + \tilde{\Delta}^{-2/3}_{R3} + ...)^4 \text{ contains} \]

\[ \sim \kappa v S \chi^\dagger \chi. \]