750 GeV Diphoton Excess Confronted with a Top-Pion in the TTM Model (Postprint)

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Full Text

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Abstract

The latest LHC data suggest an intriguing excess at $m_{\gamma\gamma} = 750$ GeV which apparently requires an explanation from beyond standard model physics. In this note we explore the possibility for this signal to arise from a top-pion in the Top Triangle Moose model, which can be viewed as a dimensional-deconstruction version of the top-color assisted technicolor model. We demonstrate that the observed excess can be accommodated by and has important implications for this interesting model.

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Introduction

Recently, the first data obtained at the LHC Run 2 with a center-of-mass energy $\sqrt{s} = 13$ TeV have been released. Interestingly, both the ATLAS and CMS collaborations have observed an excess in the diphoton invariant mass distribution around 750 GeV, with significance of 3.9σ [?] and 2.6σ [?], respectively. Interpreted in terms of a resonance induced by one (pseudo)scalar S of mass 750 GeV, this signal indicates that the production cross section times the $\gamma\gamma$ branching ratio of S has a value of $\sigma(pp \to S)\mathrm{Br}(S \to \gamma\gamma) =$ [value] fb ($\sqrt{s} = 13$ TeV ATLAS), [value] fb ($\sqrt{s} = 13$ TeV CMS). In addition, the ATLAS excess features a width of about 45 GeV at face value while the CMS excess width is narrow and inconclusive [?]. We will therefore take seriously the suggestive peak position and signal cross section, but consider the width value only as a reference in the following analysis.

If established, this excess would very likely lead us to new physics beyond the Standard Model (SM). In this connection various interesting possibilities have been proposed to explain the signal [?]. One solution of particular interest is to consider S as a composite particle due to the confinement of a new strong dynamics [?]. This idea can be traced back to technicolor (TC) theory which serves as an alternative for electroweak symmetry breaking [?]. In TC models, many massless techniquarks are generally introduced which result in a large chiral symmetry. When the chiral symmetry is spontaneously broken by techniquark condensation, some Goldstone bosons corresponding to the broken symmetries (except those corresponding to broken electroweak symmetries) will arise, which are unique composite pseudoscalar candidates. An interesting TC model is the one assisted by an additional strong interaction—top-color, as the name suggests, which only acts on the third generation quarks [?]. This model can naturally account for the largeness of m_t via top-quark condensation, while electroweak symmetry breaking still mainly comes from the conventional TC sector. Notably, there will be three additional Goldstone bosons called top-pions that correspond to the broken chiral symmetries involving t and b.

In this short note we will investigate the possibility for S to be a neutral top-pion from the Top Triangle Moose (TTM) model [?, ?], which can be viewed as a dimensional-deconstruction [?, ?] version of the top-color assisted TC model [?]. In the next section, we will first recapitulate the essential features and relevant details of the TTM model and then perform numerical analysis to show that the experimental result can be fitted. Our conclusions and some further discussions will be given in the last section.

Framework and Analysis

A. The TTM Model Revisited

The TTM model [?, ?] was originally proposed for reducing the tension between obtaining a realistic top-quark mass and fulfilling the electroweak precision measurements, which exists in the three-site Higgsless model [?]. This is achieved by separating the bulk of electroweak symmetry breaking from that of top-quark mass generation, resembling the top-color assisted TC model [?]. In the TTM model, one invokes the gauge interactions $SU(2)_0 \times SU(2)_1 \times U(1)_2$ (with respective couplings g, $\tilde{g}$ and g') under which the fermion fields furnish the following representations:

$$Q_{L0} \sim (2, 1, \tfrac{1}{6}), \quad Q_{L1} \& Q_{R1} \sim (1, 2, \tfrac{1}{6}), \quad u_{R2} \sim (1, 1, \tfrac{2}{3}), \quad d_{R2} \sim (1, 1, -\tfrac{1}{3})$$

Note that we introduce a vector-like partner for every SM fermion, which is allowed to have a mass term $M_D Q_{L1} Q_{R1}$ in the first place.

In order to break $SU(2)_0 \times SU(2)_1 \times U(1)_2$ down to electromagnetism as well as generate masses for the massless quarks, two bi-fundamental fields Σ_{01} and Σ_{12} together with a top-Higgs field Φ are introduced. While Φ carries quantum numbers $(2, 1, \frac{1}{2})$, Σ_{01} and Σ_{12} are non-linear sigma model fields with covariant derivatives:

$$D_\mu \Sigma_{01} = \partial_\mu \Sigma_{01} + i g W_0^\mu \Sigma_{01} - i \tilde{g} \Sigma_{01} W_1^\mu,$$
$$D_\mu \Sigma_{12} = \partial_\mu \Sigma_{12} + i \tilde{g} W_1^\mu \Sigma_{12} - i g' \Sigma_{12} \tau^3 B^\mu,$$

where $W_0^\mu = W_0^{a\mu} \tau^a$ and $W_1^\mu = W_1^{a\mu} \tau^a$ with $\tau^a = \sigma^a/2$ (for $a = 1, 2, 3$) being the generators of $SU(2)$. These scalar fields develop vacuum expectation values (VEVs) and can be expanded around their VEVs as follows:

$$\Sigma_{01} \sim \exp\left(\frac{i\pi^a\tau^a}{v\cos\omega}\right), \quad \Sigma_{12} \sim \exp\left(\frac{i\pi^a\tau^a}{v\cos\omega}\right),$$
$$\Phi \sim \begin{pmatrix} \frac{1}{\sqrt{2}}(f + H_t + i\pi_t^0) \\ \pi_t^- \end{pmatrix}$$

where ω parameterizes the partition of electroweak symmetry breaking (equivalently v) among the different sectors. Six combinations of the above degrees of freedom will be eaten, generating masses for the two sets of weak bosons $-W^\pm, Z^0$ and $W'^\pm, Z'^0$. There exists a mass relation between $W^\pm$ and $W'^\pm$ as given by $M_{W'}^2 = \frac{1}{4}\tilde{g}^2 v^2 \cos^2\omega$ with $g/\tilde{g}$ required to be a small quantity for phenomenological considerations (which demand $M_W \ll M_{W'}$). Hence we are left with four uneaten states, namely H_t (called top-Higgs) and one iso-triplet (called top-pions):

$$\Pi_t^0 = \pi_t^0 \cos\omega + \pi^3 \sin\omega, \quad \Pi_t^\pm = \pi_t^\pm \cos\omega + \pi^\pm \sin\omega.$$

They receive their masses mainly from the following interactions [?, ?]:

$$\mathcal{L} \supset \kappa f^2 \mathrm{Tr}\left(\Sigma_{01}\Sigma_{12}\right) + \lambda \left|\Phi^\dagger \Sigma_{01}\Sigma_{12}\Phi\right|^2.$$

A straightforward calculation gives the top-Higgs and top-pion masses as:

$$M_{H_t}^2 = 2v^2(\kappa + 4\lambda)\sin^2\omega, \quad M_{\Pi_t}^2 = 2v^2\kappa\tan^2\omega.$$

In addition, these interactions give rise to the trilinear coupling among three top-pions:

$$\mathcal{L} \supset 2i\kappa v \sin^2\omega \tan^2\omega \Pi_t^0 \Pi_t^+ \Pi_t^-$$

which will contribute to the loop process of diphoton emission.

On the other hand, Σ_{01}, Σ_{12} and Φ also contribute to fermion masses through the Yukawa interactions:

$$\mathcal{L} \supset \epsilon_L \bar{Q}_{L0}\Sigma_{01}Q_{R1} + \bar{Q}_{L1}\Sigma_{12}Q_{R2} + \lambda_u \bar{Q}_{L0}\Phi u_{R2} + \lambda_d \bar{Q}_{L0}\Phi d_{R2} + \mathrm{h.c.}$$

Here ϵ_L is a flavor-universal parameter that must be approximately $x/\sqrt{2}$ in order for the SM fermions to decouple from W' [?], while ϵ_R^f is flavor-dependent. It should be mentioned that ϵ_R^t is subject to the precision measurement constraint [?]:

$$\frac{\epsilon_R^t M_D}{16\pi^2 v^2} < 10^{-3}.$$

To mimic the role of top-color, Φ is assumed to couple preferentially with the third generation fermions, implying that only λ_t, λ_b and λ_τ of the λ_f' s are considerable. The mass matrix for t and its vector-like partner T (similarly for b and its vector-like partner B) and the resulting mass eigenvalues thus turn out to be:

$$M_t = \begin{pmatrix} 0 & \epsilon_L M_D \\ \epsilon_R^t M_D & \lambda_t v \sin\omega \end{pmatrix},$$

with eigenvalues:

$$m_t = \frac{M_D \epsilon_L \epsilon_R^t}{\sqrt{1+a^2}}, \quad m_T = M_D\sqrt{1+a^2},$$

where a stands for $\lambda_t v \sin\omega/(\sqrt{2}M_D)$. For the mass matrices of the first two generation fermions, there will not be a term like a in Eq. (13). Consequently, the mass eigenvalues for these SM fermions and their vector-like partners are approximately $M_D \epsilon_L \epsilon_R^f$ and M_D, respectively.

B. Numerical Results

Before performing numerical calculations, let us present some relevant details and useful formulas concerning the decay of Π_t^0. By inserting Eqs. (4, 6) into Eq. (11), one may easily derive the couplings between Π_t^0 and the SM fermions [**?**, **?**]:

$$\mathcal{L} \supset \frac{i}{\sqrt{2}v}\left[m_t \cot\omega\, \bar{t}_L t_R + m_b \cot\omega\, \bar{b}_L b_R + m_\tau \cot\omega\, \bar{\tau}_L \tau_R + m_c \tan\omega\, \bar{c}_L c_R\right]\Pi_t^0 + \text{h.c.}$$

The decay widths for these processes can be calculated according to:

$$\Gamma(\Pi_t^0 \to \bar{t}t) = \frac{3m_{\Pi_t}}{8\pi v^2}\cot^2\omega\, m_t^2 \beta_{tt},$$
$$\Gamma(\Pi_t^0 \to \bar{c}c) = \frac{3m_{\Pi_t}}{8\pi v^2}\tan^2\omega\, m_c^2 \beta_{cc},$$

where $\beta_{\alpha\beta}$ reads as $\beta_{\alpha\beta} = \lambda^{1/2}(1, \alpha, \beta)$, with $\lambda(\alpha, \beta) = 1 + \alpha^2 + \beta^2 - 2\alpha\beta$.

Apparently, the width of $\Pi_t^0 \to \bar{t}t$ can be comparable to and even exceed that of $\Pi_t^0 \to \bar{c}c$ when $\tan\omega$ is large enough, while the widths of $\Pi_t^0 \to \bar{b}b$ and $\Pi_t^0 \to \tau\bar{\tau}$ are always much smaller. The decays to $\bar{t}T$ and $T\bar{T}$ will also be kinematically allowed, for which the associated couplings are obtained as [**?**, **?**]:

$$\mathcal{L} \supset \bar{T}_L t_R \Pi_t^0 + \bar{t}_L T_R \Pi_t^0 + \bar{T}_L T_R \Pi_t^0 + \text{h.c.}$$

with coefficients involving combinations of ϵ_R^t, a, ω, and x.

Similar to the SM Higgs h, Π_t^0 can also decay to two photons (gluons) through charged (colored) fermion triangle loops. The corresponding decay widths are given by:

$$\Gamma(\Pi_t^0 \to \gamma\gamma) = \frac{G_\mu \alpha^2 m_{\Pi_t}^3}{128\sqrt{2}\pi^3}\left|\sum_f N_c^f Q_f^2 \alpha_f F_{1/2}(\tau_f)\right|^2,$$

$$\Gamma(\Pi_t^0 \to gg) = \frac{G_\mu \alpha_s^2 m_{\Pi_t}^3}{36\sqrt{2}\pi^3}\left|\sum_f \alpha_f F_{1/2}(\tau_f)\right|^2,$$

by analogy with those for h, with $\alpha_f \equiv \bar{g}_{\Pi_t^0 f\bar{f}}/g_{hf\bar{f}}$ being the relative coupling strength (e.g., $\alpha_t = \cot\omega$). In the above, G_μ stands for the Fermi constant 1.17×10^{-5} GeV^{-2}, whereas the symbols α, α_s, N_c and Q_f are self-explanatory. Furthermore, the loop functions $F_{1/2}(\tau)$ are given by [**?**]:

$$F_{1/2}(\tau) = 2\tau[1+(1-\tau)f(\tau)],$$

with $\tau_f \equiv m_f^2/M_{\Pi_t}^2$ and:

$$f(\tau) = \begin{cases} \arcsin^2(\sqrt{\tau}) & \text{if } \tau \le 1, \\ -\frac{1}{4}\left[\ln\frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2 & \text{if } \tau > 1. \end{cases}$$

In contrast, only $\Pi_t^\pm$ take effect via the scalar loop. In the summation over fermions, we will include t, b, c, T and τ.

In order to reproduce the observed diphoton excess in terms of the Π_t^0 resonance, one needs to have:

$$\sigma(pp\to\gamma\gamma) = \frac{\pi^2}{8m_{\Pi_t}s}\left[C_{gg}\Gamma(\Pi_t^0\to gg) + \sum_q C_{q\bar{q}}\Gamma(\Pi_t^0\to q\bar{q})\right]\mathrm{Br}(\Pi_t^0\to\gamma\gamma) \approx 10\pm3 \text{ fb}$$

for $\sqrt{s} = 13$ TeV. Here Γ is the total width of Π_t^0 and approximates to:

$$\Gamma \approx \Gamma(\Pi_t^0\to t\bar{t}) + \Gamma(\Pi_t^0\to b\bar{b}) + \Gamma(\Pi_t^0\to c\bar{c}) + \Gamma(\Pi_t^0\to \tau\bar{\tau}) + \Gamma(\Pi_t^0\to gg) + \Gamma(\Pi_t^0\to \bar{t}T) + \Gamma(\Pi_t^0\to T\bar{T}),$$

while C_{gg} and $C_{q\bar{q}}$ are the dimensionless partonic integral functions [**?**]:

$$C_{gg} = \int_0^1 dx \int_0^1 dy \frac{g(x)g(y)}{xy}\delta(xy-\tau_{\Pi_t}),$$
$$C_{q\bar{q}} = \int_0^1 dx \int_0^1 dy \frac{q(x)\bar{q}(y)+\bar{q}(x)q(y)}{xy}\delta(xy-\tau_{\Pi_t}),$$

with $\tau_{\Pi_t} = m_{\Pi_t}^2/s$.

Now, we proceed to study whether the neutral top-pion Π_t^0 can serve as a candidate for the observed resonance at 750 GeV. First, we find the parameter space for Π_t^0 to give a signal consistent with Eq. (21). There are four free parameters –$\sin\omega$, ϵ_R^t, $M_{W'}$ and M_D–relevant for our study. The allowed parameter space of $\sin\omega$ and ϵ_R^t is shown in Fig. 1. In this calculation, we have imposed the constraint in Eq. (12) and allowed $M_{W'}$ and M_D to vary in the range $[300, 1000]$

GeV. As one can see from Fig. 1, $\sin\omega$ must lie in a range extremely close to 1 while ϵ_R^t ranges from 0.3 to 0.7.

In Fig. 2 we present the cross sections of $pp \to jj, \gamma\gamma, t\bar{t}, b\bar{b}, \tau\tau$ (where jj includes gg and $c\bar{c}$) at $\sqrt{s} = 13$ TeV against each of the four parameters when the other three are fixed to particular values. It is apparent that these cross sections are more sensitive to $\sin\omega$ and ϵ_R^t than to the mass parameters $M_{W'}$ and M_D. In particular, the cross section for $pp \to \gamma\gamma$ can be enhanced by increasing $\sin\omega$ and ϵ_R^t. The upper limits for the cross section of each decay mode are also shown, extrapolated from LHC searches at $\sqrt{s} = 8$ TeV [?]. One can see that the phenomenological consequences of a 750 GeV Π_t^0 are compatible with these constraints.

Finally, we plot the possible total decay width of Π_t^0 as a function of $\sin\omega$ in Fig. 3. In most of the allowed parameter space, Γ is within 30 GeV, in agreement with the observed width. But as $\sin\omega$ decreases from 1, Γ grows rapidly, rendering the signal for $\sigma(gg \to \gamma\gamma)$ unobservable.

Let us briefly discuss the properties of $\Pi_t^\pm$. An interesting consequence of the TTM model is that it predicts $\Pi_t^\pm$ to have the same mass as Π_t^0 and H_t (i.e., 750 GeV). On the other hand, the corresponding couplings for $\Pi_t^\pm$ are given by:

$$\mathcal{L} \supset \frac{i}{\sqrt{2}v}\left[m_t \cot\omega\, \bar{t}_R b_L + m_b \cot\omega\, \bar{t}_L b_R + m_\tau \cot\omega\, \bar{\nu}_\tau L_\tau R + m_c \tan\omega\, \bar{c}_L s_R\right]\Pi_t^+ + \text{h.c.}$$

One immediately finds that the dominant decay channel of Π_t^+ will be $\Pi_t^+ \to t\bar{b}$ or $c\bar{s}$, depending on the value of $\sin\omega$. Accordingly, $\Pi_t^\pm$ can mainly be produced in association with a quark via the process $gb \to \Pi_t^+ t$ or $gs \to \Pi_t^+ c$, while contributions from electroweak processes such as $u\bar{d} \to \Pi_t^+$ are negligibly small. By comparing Fig. 10 and Fig. 13 of Ref. [?], we can see that the production cross section for $\Pi_t^\pm$ is about one order of magnitude smaller than that for Π_t^0. In combination with the fact that the dominant decay channels of $\Pi_t^\pm$ are hadronic and tend to be masked by high backgrounds, this means that a direct search for $\Pi_t^\pm$ is difficult at the present stage.

Last but not least, we point out that H_t is a unique candidate for the 125 GeV resonance discovered in 2012 [?, ?], which is widely believed to be the SM Higgs boson. The reason lies in the fact that in the preferred parameter space region where $\sin\omega \approx 1$, electroweak symmetry breaking mainly originates from a non-vanishing VEV of the top-Higgs field Φ, leading H_t to behave similarly to the SM Higgs boson. The latter point can be easily seen from the coupling strengths between H_t and SM particles. For instance, the coupling strength for $H_t W^+ W^-$ is approximately $g^2 v \sin\omega/2$ [?, ?], which reduces to the SM case when $\sin\omega = 1$. In addition, from Eq. (9) one can see that H_t has a mass suppressed by $\cos\omega$ (which takes a value ~ 0.1 in the viable parameter space region) compared to $M_{\Pi_t} = 750$ GeV, in good qualitative agreement with experimental results.

Quantitatively, one always has the freedom to specify a suitable value for λ in Eq. (9) to obtain a 125 GeV H_t precisely.

Summary

While the 750 GeV diphoton excess necessitates further data collection to be confirmed or ruled out, it is still worthwhile to explore various new physics scenarios that can naturally account for this signal and their physical implications. Motivated by the possibility that this excess may be due to a composite (pseudo)scalar of mass around 750 GeV, we investigate whether TC models can accommodate such a signal and find that a variety of TC models are unable to fit the experimental result. These specific models include the original one-family model of FS [?], variant one-family model [?], LR multiscale model [?], TC Straw Man model low scale [?], MR Isotriplet model [?], and top-color assisted TC models [?]. Most of these models have too large a width for Π_t^0 or too small a cross section to give a satisfying result. Only in the variant one-family model can the total width of Π_t^0 be lowered to ~ 45 GeV, but at this point the cross section is smaller than the observed signal by two orders of magnitude.

Most of our attention has been paid to the TTM model, which is phenomenologically viable. It is found that identifying Π_t^0 as the reported resonance has important implications: the parameter space (particularly for $\sin\omega$) is strongly constrained, making the model more predictive. Hence we may confirm or rule out the possibility of Π_t^0 being the 750 GeV resonance by paying particular attention to this channel. Furthermore, the TTM model predicts two charged top-pions $\Pi_t^{\pm}$ of the same mass as Π_t^0. Unfortunately, they are difficult to discover owing to a combination of low production cross section and high backgrounds for their decay products [?]. Finally, it is interesting to note that H_t may serve as a unique candidate for the observed 125 GeV resonance. To summarize, the TTM model can explain the recently observed diphoton excess and has testable predictions, thereby deserving further attention.

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Note: Figure translations are in progress. See original paper for figures.