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Interpreting 750 GeV diphoton excess in SU(5) grand unified theory

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ABSTRACT

The ATLAS and CMS experiments at the LHC have found significant excess in the diphoton invariant mass distribution near 750 GeV. We interpret this excess in a predictive nonsupersymmetric SU(5) grand unified framework with a singlet scalar and light adjoint fermions. The 750 GeV resonance is identified as a gauge singlet scalar. Both its production and decays are induced by 24 dimensional adjoint fermions predicted within SU(5). The adjoint fermions are assumed to be odd under Z_2 symmetry which forbids their direct coupling to the standard model fermions. We show that the observed diphoton excess can be explained with sub-TeV adjoint fermions and with perturbative Yukawa coupling. A narrow width scenario is more preferred while a simultaneous explanation of observed cross section and large total decay width requires some of the adjoint fermions lighter than 375 GeV. The model also provides a singlet fermion as a candidate of cold dark matter. The gauge coupling unification is achieved in the framework by introducing color sextet scalars while being consistent with the proton decay constraint.

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1. Introduction

The first set of data collected by ATLAS and CMS experiments at the Large Hadron Collider (LHC) with proton–proton collisions at center-of-mass energy $\sqrt{s} = 13$ TeV has recently been presented by the respective collaborations [1]. Both the experiments claim an excess in the diphoton channel at the invariant mass near 750 GeV. This result is based on 3.2 fb^{-1} and 2.6 fb^{-1} of integrated luminosities collected by the ATLAS and CMS respectively. It has the local statistical significance of 3.9σ and 2.6σ respectively. The excess around the same mass has not been seen in any other channels like dijet, dilepton or diboson. Also, the similar excess was not seen even in diphoton channel in the previous run with $\sqrt{s} = 8$ TeV. The new excess is best described by relative width $\Gamma/M \approx 0.06$ as suggested by the ATLAS Collaboration while the same hypothesis by the CMS Collaboration reduces the significance of excess to 2.0σ [1]. Based on the claimed width, the estimated cross section is given as [1,2]

$$\begin{aligned} \sigma(pp \rightarrow X \rightarrow \gamma\gamma) &\approx (10 \pm 3) \text{ fb} \quad \text{by ATLAS [1]}, \\ &\approx (6 \pm 3) \text{ fb} \quad \text{by CMS [1]}, \end{aligned} \quad (1)$$

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where X represents a new intermediate massive state with mass $M \approx 750$ GeV.

It is quite possible that the above experimental result is just a statistical fluctuation and more data may eventually wipe out this primitive signal. However, if confirmed, this will be the first direct observation of sub TeV scale physics beyond the Standard Model (SM). While the more LHC data will decide the fate of this signal, it is interesting to interpret this signal in the context of currently known new physics scenarios and if the viability of new models can be tested using this new resonance. Several proposals have already been forwarded in this direction [2–7]. A new particle decaying into two photons can be of either spin-0 or spin-2. Assuming X as spin-0 s -channel resonance, as either a singlet or a weak doublet under the SM, the observed large cross section cannot be explained with the only SM degrees of freedom [3,4]. This includes class of models with only extra uncolored scalars including two Higgs doublet models. One of the modification to these simple scenarios is to add extra vector-like fermions which can contribute in both production and decay of this heavy scalar state [2–4,6]. The colored fermions with large electric charges can account for large cross section observed at the LHC. In typical bottom-up approaches suggested so far, a choice of such new vector-like fermions is quite ad hoc and there exist many possible candidates to account for the diphoton signal [4,6].

In this paper, we present a model based on a well motivated class of nonsupersymmetric SU(5) grand unified theory [8] and show that the diphoton excess can be accounted using a scalar

singlet, namely S of mass $M = 750$ GeV and light (sub TeV) fermions residing in a 24 dimensional adjoint representation of SU(5). The adjoint fermions arise in the SU(5) GUT with fixed gauge charges and one does not need to introduce ad hoc vector-like fermions as it has been done in several works listed [6]. We propose a renormalizable version of theory which provides predictive framework to account for diphoton excess in terms of finite number of vector-like fermions and with their unified Yukawa interactions with a scalar S . The adjoint fermions are kept odd under Z_2 symmetry and they have only gauge interactions and Yukawa interactions with S . All the tree level decays of S into the SM fermions are forbidden by the gauge and discrete Z_2 symmetries. The scalar S can be produced through gluon–gluon fusion at 1-loop and also can decay into two photons through similar triangle diagrams with adjoint fermions in the loop. We show that such a framework can account for large enough cross section of diphoton events observed at the LHC. We discuss both the narrow and broad width scenarios of diphoton excess provided by the different ranges of the masses of adjoint fermions. Because of the presence of an unbroken Z_2 symmetry, model also provides a candidate for fermionic cold dark matter. Further, we show how gauge coupling unification can be achieved in this model using light adjoint fermions and a couple of light colored scalar fields being consistent with the proton decay constraints.

We describe the model in the next section. In section 3, we discuss how the diphoton excess can be fitted in the model. The gauge coupling unification and constraints from proton decay are discussed in section 4. Finally, we summarize in section 5.

2. The model

We assume that the 750 GeV resonance seen at the LHC is a singlet scalar under the SM. Implementing it in SU(5), we assume that it is also a singlet under SU(5). Its production and decays are mediated by the vector-like fermions which belong to an adjoint of SU(5), namely 24_F . We impose a discrete Z_2 symmetry under which 24_F is odd while all the other fields are even. The SM fermions are accommodated in a fundamental and in an antisymmetric representations of SU(5) as $\bar{5}_F$ and 10_F respectively [8]. The consistent gauge symmetry breaking down to the $SU(3)_C \times U(1)_{em}$ and viable charged fermion masses are generated by introducing 5_H , 24_H and 45_H scalars. The 45_H is needed to remove the degeneracy between the masses of charged leptons and down-type quarks at the renormalizable level [9,10]. The gauge and Yukawa interactions follow in the standard way [8,10]. The renormalizable scalar Lagrangian of the model can be written as

$$\mathcal{L}_{\text{scalar}} = \frac{M_S}{2} S^2 + \lambda S^4 + \mathcal{L}(5_H, 24_H, 45_H, S), \quad (2)$$

where $\mathcal{L}(5_H, 24_H, 45_H, S)$ is the Lagrangian including the scalar fields 5_H , 24_H and 45_H written in standard way [8,10] with their additional interactions with singlet. The GUT symmetry breaking is induced by the vacuum expectation value (vev) of 24_H preserving the SM gauge symmetry. For this to happen, a suitable choice for vev is $\langle 24_H \rangle = \text{Diag.}(2, 2, 2, -3, -3)v/\sqrt{30}$. The 5_H and 45_H each contains SM like Higgs doublets which get mixed with each other and one of the linear combinations remains light that can be identified as the SM Higgs boson. Note that a fine tuning is needed to arrange such a light Higgs doublet while keeping the other multiplets in 5_H and 45_H as heavy as the GUT scale. We assume such fine tuning in the model. The minimal version of renormalizable SU(5) does not account for neutrino masses. This can easily be solved by adding either singlet fermion or 15_H [11] and inducing small neutrino masses through type I or type II seesaw mechanisms respectively.

The 24_F fermions have the standard gauge interactions. In the absence of Z_2 symmetry, they also have Yukawa interactions with the SM fermions through a gauge invariant term like $\bar{5}_F 24_F 5_H$. Such interactions result into the mixing between the SM fermions and adjoint fermions after electroweak symmetry breaking (EWSB) and lead to tree level decays of S into the SM fermions. Since there already exist strong bounds on such decays from 8 TeV LHC [2], we forbid such interactions through a Z_2 symmetry under which 24_F is odd. Besides the usual kinetic terms, the renormalizable interaction of 24_F with the other fields in the model can be written as

$$\mathcal{L}_{24_F} = m_F \text{Tr}(24_F^2) + \lambda_H \text{Tr}(24_F^2 24_H) + \lambda_S S \text{Tr}(24_F^2). \quad (3)$$

After SU(5) breaking through the vev of 24_H , the first and second terms determine the mass spectrum of the various adjoint fermions residing in 24_F while the last term gives required interaction between adjoint fermions and a scalar of $M_S = 750$ GeV. Under the SM gauge group, the 24_F decomposes as:

$$24_F = Q_8(8, 1, 0) + Q_3(3, 2, -5/6) + \bar{Q}_3(\bar{3}, 2, 5/6) + L_3(1, 3, 0) + L_1(1, 1, 0). \quad (4)$$

Here the first (second) index in the bracket indicates $SU(3)_C$ ($SU(2)_L$) representation of corresponding fermion while the last index is the hypercharge Y . The hypercharge is normalized such that the electric charge is given as $Q = T_{3L} + Y$. Once the electroweak symmetry is broken, we have adjoint fermions Q_8^0 , L_1^0 , L_3^0 , L_3^\pm , $Q_3^{\pm 1/3}$ and $Q_3^{\pm 4/3}$ where the superscript indicates the electric charge. All these fermions couple to the scalar S and can contribute into the production and decay of S through the 1-loop triangle diagrams.

Let us now discuss the mass spectrum of the 24_F fermions. All the multiplets within 24_F have a common mass m_F which gets corrected after SU(5) is broken into the SM through a vev, $\langle 24_H \rangle = \text{Diag.}(2, 2, 2, -3, -3)v/\sqrt{30}$. After EWSB, one gets

$$\begin{aligned} m_{Q_8} &= m_F + \frac{2}{\sqrt{30}} \lambda_H v, \\ m_{Q_3, \bar{Q}_3} &= m_F - \frac{1}{2\sqrt{30}} \lambda_H v, \\ m_{L_3} &= m_F - \frac{3}{\sqrt{30}} \lambda_H v, \\ m_{L_1} &= m_F - \frac{1}{\sqrt{30}} \lambda_H v. \end{aligned} \quad (5)$$

Clearly, one can obtain the desired masses for any two multiplets using the free parameters while the masses of remaining fermions get fixed. All the multiplets however couple to S with a universal coupling λ_S . Our aim in this paper is to investigate the viability of the fermions within 24_F in explaining the observed $\sigma(pp \rightarrow S \rightarrow \gamma\gamma)$. Before we carry out such an analysis in the next section, let us discuss below some salient features of the presented model.

- In order to explain the diphoton excess, the masses of adjoint fermions have to be much smaller than the GUT scale. One therefore has to assume that M_S , $m_F \ll M_{\text{GUT}}$ and λ_H is vanishingly small for sub TeV S and 24_F .
- The new 750 GeV scalar S can be produced at the LHC dominantly through gluon fusion mediated by Q_8^0 , $Q_3^{\pm 1/3}$ and $Q_3^{\pm 4/3}$. Its decay into a pair of photons is dominantly mediated by $Q_3^{\pm 4/3}$ and $L_3^{\pm 1}$. Hence the same set of adjoint fermions gives rise to the observed $\sigma(pp \rightarrow S \rightarrow \gamma\gamma)$. This provides a very predictive framework for 750 GeV resonance since there

is a unique coupling between various adjoint fermions and S and the masses of various adjoint fermions are also correlated as can be seen from Eq. (5).

- The neutral fermion L_1^0 can serve as a cold dark matter candidate in this model since its stability is guaranteed by an unbroken Z_2 symmetry. If the mass of L_1^0 is smaller than $M_S/2$, then S can decay into a pair of L_1^0 giving missing transverse momentum signal at the LHC. As we show later, both the scenarios are open in which L_1^0 could be lighter or heavier than $M_S/2$. In the later case, the dark matter can co-annihilate into the SM particles through S and adjoint fermions. We leave further studies of dark matter abundance and constraints from direct and indirect search experiments for future investigations.
- Note that S can decay into a pair of the SM Higgs bosons through $\mu_H S S_H^\dagger S_H$ term in the scalar potential. In order to evade the current limits on such decays, one can assume small enough coupling μ_H without affecting the other phenomenological aspects of the model. The most stringent bound on this coupling currently comes from the diHiggs production at 8 TeV LHC [12]. In this model, the diHiggs production is dependent on two parameters, the Yukawa coupling λ_S in the production of S , and coupling μ_H in the decay. For $\lambda_S = 1.0$ and 0.5, the most stringent upper bounds on μ_H are estimated to be 100 GeV and 400 GeV respectively.
- The Z_2 parity forbids the direct interactions between the 24_F and SM fermions. In the absence of such symmetry 24_F and $\bar{5}_F$ can have Yukawa interactions through 5_H . This can lead to neutrino masses through type III (fermion triplet mediated) seesaw mechanism as discussed in [13]. This scenario can also be a candidate model for diphoton excess however the constraints on S decaying into the pair of SM fermions should be taken into account since such decays are now induced due to mixing between the 24_F and SM fermions.

3. Fitting diphoton excess

The observed cross section for the diphoton excess is quite large ~ 10 fb. It is quite clear that this excess cannot be explained only through the contributions of the top quarks and W bosons in the loops even if a new scalar is charged under the SM. Thus, this resonance cannot be due to the only new scalar and should be accompanied by other new states such as the vector-like fermions [6]. A model proposed in the previous section naturally contains such vector-like fermions that includes three colored particles, namely Q_8^0 , $Q_3^{\pm 1/3}$ and $Q_3^{\pm 4/3}$ and one colorless charged particle L_3^\pm . Since S is a singlet scalar, it does not have tree level interactions with the SM fermions and gauge bosons. Thus, it can only be produced through the gluon-fusion at loop level. Since it is a gluon-initiated loop, only colored particles will contribute in the production of S .

The partonic $gg \rightarrow S$ production can be written in the standard form in terms of $\Gamma(S \rightarrow gg)$ decay width as [14]:

$$\hat{\sigma}(gg \rightarrow S) = \frac{\pi^2}{8M_S} \Gamma(S \rightarrow gg) \delta(\hat{s} - M_S^2), \quad (6)$$

where, the decay width of $\Gamma(S \rightarrow gg)$ is given by [14,2]

$$\Gamma(S \rightarrow gg) = M_S \frac{\alpha_s^2}{2\pi^3} \left| \sum_f C_{rf} \sqrt{x_f} \lambda_S \mathcal{A}(x_f) \right|^2. \quad (7)$$

Here $C_3 = 1/2$ for the triplet and $C_8 = 3$ for the octet fermions. The $x_f = 4M_f^2/M_S^2$, $\mathcal{A}(x_f) = 1 + (1 - x_f) \arctan^2(1/\sqrt{x_f - 1})$, and M_f is the mass of adjoint fermion propagating in the loop. The sum

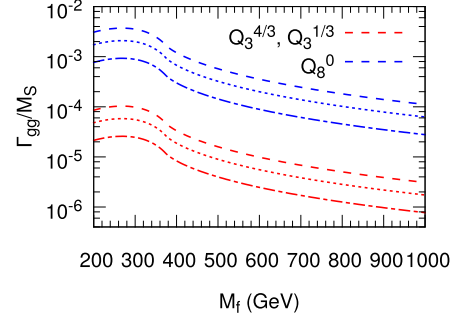


Fig. 1. The Γ_{gg}/M_S for colored states: octet Q_8 (blue) and triplet Q_3 (red). Also shown are the contributions for three values of Yukawa coupling $|\lambda_S| = 1.0$ (long-dashed), 0.75 (short-dashed) and 0.5 (long-short dashed). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

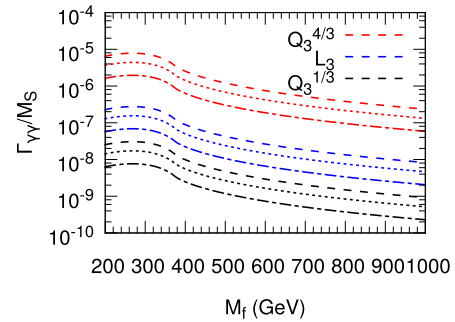


Fig. 2. The $\Gamma_{\gamma\gamma}/M_S$ for electrically-charged states: $Q_3^{\pm 4/3}$ (red), $Q_3^{\pm 1/3}$ (black) and L_3^\pm (blue). Also shown are the contributions for three values of Yukawa coupling $|\lambda_S| = 1.0$ (long dashed), 0.75 (short-dashed) and 0.5 (long-small dashed). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

runs over all the colored states present in the model. The partonic cross section can easily be transformed into hadronic cross section by multiplying the integrated gluon-luminosities at 13 TeV. We find that the largest contribution to the production of S comes from color octet Q_8^0 because of large factor of $C_8 = 3$ as compared to $Q_3^{\pm 1/3}$ and $Q_3^{\pm 4/3}$. Fermions $Q_3^{\pm 1/3}$ and $Q_3^{\pm 4/3}$, being color triplets, contribute equally to the production. In Fig. 1, we show the contributions of Q_8^0 , $Q_3^{\pm 1/3}$ and $Q_3^{\pm 4/3}$ to Γ_{gg}/M_S for three different values of Yukawa coupling $|\lambda_S| = 1.0$ (long-dashed), 0.75 (small-dashed) and 0.5 (long-small dashed) respectively. The Γ_{gg}/M_S is about an order magnitude larger for Q_8^0 than it is for $Q_3^{\pm 1/3}$ and $Q_3^{\pm 4/3}$.

The decay width of $S \rightarrow \gamma\gamma$ can be written as [14,2]

$$\Gamma(S \rightarrow \gamma\gamma) = M_S \frac{\alpha_{em}^2}{16\pi^3} \left| \sum_f d_{rf} Q_f^2 \sqrt{x_f} \lambda_S \mathcal{A}(x_f) \right|^2, \quad (8)$$

where for triplet $d_r = 3$ and Q_f is the electric charge of the particle. In the adjoint of $SU(5)$, there are three electrically-charged particles. The largest contribution to diphoton decay width will come from $Q_3^{\pm 4/3}$ followed by L_3^\pm and $Q_3^{\pm 1/3}$. The contribution of $Q_3^{\pm 4/3}$ is nearly 1/9 of L_3^\pm to diphoton width while that of $Q_3^{\pm 4/3}$ is 256/9 of L_3^\pm . In Fig. 2, we show the contributions of $Q_3^{\pm 1/3}$, $Q_3^{\pm 4/3}$ and L_3^\pm to $\Gamma_{\gamma\gamma}/M_S$ for three different values of the Yukawa coupling $|\lambda_S| = 1.0$ (long dashed), 0.75 (small-dashed) and 0.5 (long-small dashed).

We now discuss the cross section $\sigma(pp \rightarrow S \rightarrow \gamma\gamma)$ predicted in the model. In Fig. 3, we show the production cross section of S

times the branching fraction in femtobarns in the plane of adjoint fermion masses and universal Yukawa coupling $|\lambda_S|$. For simplicity, we consider all adjoint fermions to be degenerate in masses and combine their contributions. The light blue region corresponds to 2.5–5 fb, the dark blue to 5–7.5 fb, dark green to 7.5–10 fb and light green to 10–12.5 fb of cross section of $pp \rightarrow S \rightarrow \gamma\gamma$. All these regions are compatible with the cross section measured by the ATLAS and CMS for the 750 GeV diphoton resonance as listed in Eq. (1). We also have implemented the model in MadGraph [15] using Feynrules [16] and all the numbers for cross section and decay widths have been cross checked with MadGraph.

The broad width scenario preferred by the ATLAS analysis requires the tree level decays of S . If the masses of adjoint fermions $M_f > M_S/2$, then S decays only into gg and $\gamma\gamma$ through loops. In such a scenario, the total width of the resonance is very small $\sim \mathcal{O}$ (MeV). Note that $S \rightarrow hh$ decay is still open but it is induced by a coupling different than λ_S as discussed in the previous section. We assume that such coupling is small enough and, thus, this channel is sub-dominant compared to gg and $\gamma\gamma$ respecting the 8 TeV constraints on $S \rightarrow hh$. In such a scenario, only a few MeV of width can be achieved. Thus this scenario leads us to the narrow width of S which is not yet conclusively disfavored by the data. The $\text{BR}(S \rightarrow \gamma\gamma)$ is much larger for this mass range of adjoint fermions which allows values of coupling $|\lambda_S|$ to be as small as $\sim \mathcal{O}(0.3)$ to explain the observed diphoton excess as it can be seen from Fig. 3.

On the other hand, when $M_f < M_S/2$, the tree-level decays of S into a pair of adjoint fermions open up and thereby increasing

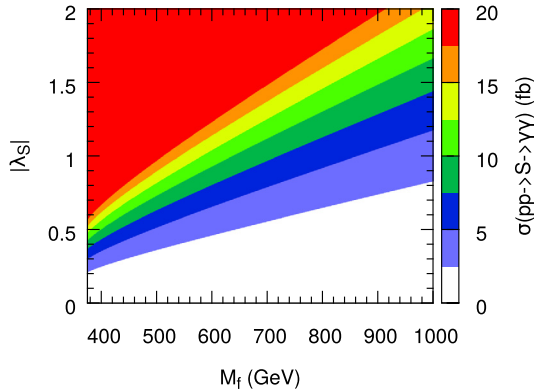


Fig. 3. The production cross section of S times the $\text{BR}(S \rightarrow \gamma\gamma)$ in the plane of common adjoint fermion mass M_f and universal Yukawa coupling $|\lambda_S|$ for $M_f > M_S/2$. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

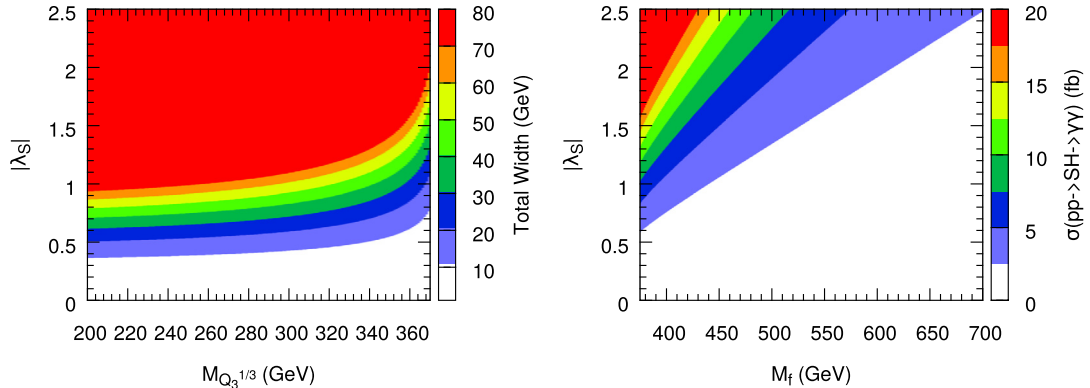


Fig. 4. Left Panel: The total decay width of the scalar S in the plane of adjoint fermion mass $M_{Q_3^{\pm 1/3}}$ and universal Yukawa coupling $|\lambda_S|$ for $M_{Q_3^{\pm 1/3}} < M_S/2$. Right Panel: $\sigma(pp \rightarrow \gamma\gamma)$ in the plane of heavy fermion masses and Yukawa coupling $|\lambda_S|$.

significantly the total width of S . Thus, the $\text{BR}(S \rightarrow \gamma\gamma)$ gets reduced in this mass range. As we discuss in the next paragraph, there exist direct search constraints on the masses of vector-like fermions from the LHC Run-I. It allows a possibility in which $M_{Q_3^{\pm 1/3}} < M_S/2$ while the rest of the charged particle masses are restricted to be higher than $M_S/2$. In such a scenario, the scalar S would decay into a pair of $Q_3^{\pm 1/3}$ at the tree level. Thus the width of the S around 45 GeV could also be achieved. In the left panel of Fig. 4, we show the variation of total width of S in the plane of $M_{Q_3^{\pm 1/3}}$ and $|\lambda_S|$. We keep $M_{Q_3^{\pm 1/3}} < M_S/2$ and mass of all other fermions at 500 GeV. It can be seen that it is indeed possible to obtain the decay width up to 45 GeV for $0.8 > |\lambda_S| > 0.7$ and for $M_{Q_3^{\pm 1/3}}$ between 200 GeV–320 GeV. For the mass larger than 350 GeV, one needs relatively larger values of $|\lambda_S|$. In the right panel of Fig. 4, we show the $\sigma(pp \rightarrow S \rightarrow \gamma\gamma)$ for this scenario in the plane of fermion mass M_f and the Yukawa coupling λ_S . We keep $M_{Q_3^{\pm 1/3}} = 370$ GeV and a common mass M_f for remaining fermions. In this case, because of the large tree-level decay width of $S \rightarrow Q_3^{1/3} Q_3^{-1/3}$, the $\text{BR}(S \rightarrow \gamma\gamma)$ gets reduced. Thus, one needs a large λ_S coupling so that an appropriate diphoton cross section can be obtained. Clearly, the simultaneous explanation of large total decay width and large cross section requires very special values of masses for the vector-like fermions and universal Yukawa coupling. As can be seen from Fig. 4, it can be achieved if $M_{Q_3^{\pm 1/3}} \approx 370$ GeV, $M_f \approx 400$ GeV and $|\lambda_S| \approx 1.2$.

The heavy adjoint fermions Q_3 , \bar{Q}_3 and L_3 possess non-trivial $\text{SU}(2)_L$ charges and hence they can induce decays like $S \rightarrow ZZ$, $S \rightarrow WW$ and $S \rightarrow Z\gamma$ at loop-level. We estimate the strengths of these decays in our model and compare them with the experimental constraints. In an effective theory at the electroweak scale, the leading order operators involving interactions between S and SM gauge bosons can be written as

$$\mathcal{L} = \kappa_1 S B_{\mu\nu} B^{\mu\nu} + \kappa_2 S W_{\mu\nu}^i W^{i\mu\nu} + \kappa_3 S G_{\mu\nu}^a G^{a\mu\nu}, \quad (9)$$

where $G_{\mu\nu}^a$, $W_{\mu\nu}^i$ and $B_{\mu\nu}$ are field strength tensors of the gauge bosons of $\text{SU}(3)_C$, $\text{SU}(2)_L$ and $\text{U}(1)_Y$ groups with $i = 1, 2, 3$ and $a = 1, \dots, 8$. The couplings $\kappa_i = \kappa'_i \mathcal{A}(x_f)$ and κ'_i for various adjoint fermions are listed in Table 1. We use the low-energy Higgs theorem derived in [17] to derive the coefficients κ'_i for effective scalar-diboson vertex. We use $\text{SU}(5)$ normalization $g_Y = \sqrt{3/5} g_1$ where g_1 is the coupling which unifies with g_2 and g_3 at the unification scale.

In the basis of physical gauge boson fields, the effective couplings between S and various physical gauge bosons are given as

Table 1
Effective couplings κ'_i induced by various adjoint fermions in loop.

Fermions	κ'_1	κ'_2	κ'_3
Q_8	0	0	$\frac{\lambda_S}{8\pi^2} \frac{g_3^2}{m_{Q_8}}$
(Q_3, \bar{Q}_3)	$\frac{25\lambda_S}{72\pi^2} \frac{g_3^2}{m_{Q_3}}$	$\frac{\lambda_S}{8\pi^2} \frac{g_3^2}{m_{Q_3}}$	$\frac{\lambda_S}{12\pi^2} \frac{g_3^2}{m_{Q_3}}$
L_3	0	$\frac{\lambda_S}{12\pi^2} \frac{g_3^2}{m_{L_3}}$	0
L_1	0	0	0

$$\kappa_{\gamma\gamma} = \kappa_1 \cos^2 \theta_W + \kappa_2 \sin^2 \theta_W,$$

$$\kappa_{ZZ} = \kappa_2 \cos^2 \theta_W + \kappa_1 \sin^2 \theta_W,$$

$$\kappa_{WW} = 2\kappa_2,$$

$$\kappa_{Z\gamma} = (\kappa_2 - \kappa_1) \sin 2\theta_W, \quad (10)$$

where θ_W is the weak mixing angle. The ratio of the decay widths is simply determined as $\Gamma(S \rightarrow AB)/\Gamma(S \rightarrow \gamma\gamma) = |\kappa_{AB}|^2/|\kappa_{\gamma\gamma}|^2$. In the simple case of degenerate adjoint fermions i.e. $m_{Q_3} = m_{L_3} = M_f$, these ratios are estimated as

$$\begin{aligned} \frac{\Gamma(S \rightarrow WW)}{\Gamma(S \rightarrow \gamma\gamma)} &= 10.5, & \frac{\Gamma(S \rightarrow ZZ)}{\Gamma(S \rightarrow \gamma\gamma)} &= 2.0, & \text{and} \\ \frac{\Gamma(S \rightarrow Z\gamma)}{\Gamma(S \rightarrow \gamma\gamma)} &= 0.5. \end{aligned} \quad (11)$$

No resonance for 750 GeV scalar S is seen in WW , ZZ and $Z\gamma$ channels so far by the ATLAS and CMS. Using the $\sqrt{s} = 8$ TeV ATLAS data and assuming the production cross section of S grows as $r = \sigma_{13 \text{ TeV}}/\sigma_{8 \text{ TeV}} \approx 5$, the upper bounds on partial decay width of S in various final states are derived at 95% confidence level in Table I of [2]. The current bounds are $\Gamma(S \rightarrow WW)/\Gamma(S \rightarrow \gamma\gamma) \leq 20$, $\Gamma(S \rightarrow ZZ)/\Gamma(S \rightarrow \gamma\gamma) \leq 6$ and $\Gamma(S \rightarrow Z\gamma)/\Gamma(S \rightarrow \gamma\gamma) \leq 6$. The ratios estimated in Eq. (11) assuming degenerate adjoint fermions are well within the current experimental bounds. Further, all the three ratios can be lowered if $m_L \gg m_{Q_3}$ without decreasing diphoton rate as the largest contribution in $\Gamma(S \rightarrow \gamma\gamma)$ arises from Q_3 and \bar{Q}_3 .

We now briefly comment on the direct search constraints on vector-like fermions considered in this paper. The most stringent constraints on these fermions come from the searches of long-lived particles at the 7 and 8 TeV LHC by the CMS [18]. In these searches, the CMS Collaboration has utilized detector signatures like long time-of-flight to the outer muon system and anomalously high (or low) energy deposition in the inner tracker. These bounds are model independent and are only dependent on electric charges of the particles. Thus, constraints on the small electric charge particles are less stringent. As the electric charge increases, the bounds get stronger. For example, a lower bound on $Q = \pm 1/3$ particle is around 200 GeV, on $Q = \pm 1$ is around 400 GeV and on $Q = \pm 4/3$ is around 500 GeV. Therefore, only $Q_3^{\pm 1/3}$ can have mass smaller than $M_S/2$ among the adjoint fermions provided in the model. The bound on Q_8^0 can be obtained from long-lived gluino searches which is about 1.2 TeV. Considering these bounds, it is still possible to explain the observed cross section of diphoton events. As it can be seen from Fig. 3, even for very heavy fermions of masses ~ 1 TeV, the experimental result can be well explained albeit with relatively larger Yukawa couplings of $\sim \mathcal{O}(1)$. The narrow width for S turns out to be more favorable in this case.

4. Gauge coupling unification and proton decay

Before discussing a possibility of gauge coupling unification in our framework, we briefly review the problem of unification in nonsupersymmetric GUT. As it is well known in the SM, the weak

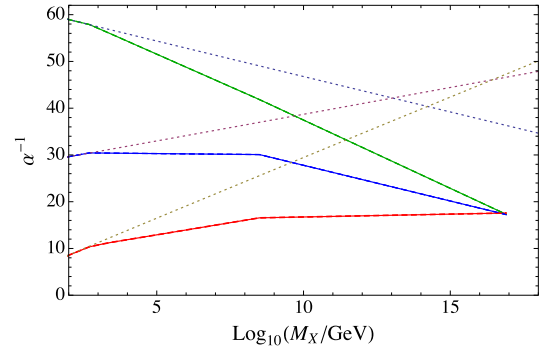


Fig. 5. Gauge coupling unification obtained by solving two loop RGE equations in the model (shown with solid lines) with degenerate adjoint fermions with mass 500 GeV and the scalars $(\bar{6}, 1, -1/3)$ and $(\bar{6}, 3, -1/3)$ with masses 2 TeV and 3.2×10^8 GeV respectively. The dotted lines correspond to running gauge couplings in the Standard Model.

and strong gauge couplings unify at $\sim 10^{15}$ GeV which is an ideal scale considering the proton decay constraints. However, the $U(1)$ gauge coupling meets the weak coupling at $\sim 10^{13}$ GeV spoiling the complete unification [19]. Adding a complete $SU(5)$ multiplet below the GUT scale do not solve this problem as, at one loop of renormalization group evolution (RGE), it only changes the value of unified gauge coupling. We check that this problem continues at two loop also. Hence the 24_F at the sub TeV scale do not really address the gauge coupling unification problem. One needs light incomplete set of multiplets to achieve gauge coupling unification. One such possibility was discussed by us in [20] where the unification was achieved with TeV scale color sextet scalars. We find that the same set of scalars can give gauge coupling unification together with light 24_F . The new scalars transform as $(\bar{6}, 1, -1/3)$ and $(\bar{6}, 3, -1/3)$ under the SM gauge symmetry. The mass of weak singlet is required in the TeV range while the weak triplet can have mass in the range 10^8 – 10^9 GeV [20]. For simplicity, we consider all the adjoint fermions residing in 24_F to be degenerate in masses and such mass can be anything in between M_Z and M_{GUT} , without spoiling the gauge coupling unification. As explained earlier, its main effect is in changing the value of the unified gauge coupling. Note that it is possible to obtain degenerate adjoint fermions assuming λ_H vanishingly small in Eq. (5). The existence of the gauge coupling unification is illustrated in Fig. 5.

We perform a two loop RGE analysis by choosing the scalars $(\bar{6}, 1, -1/3)$ and $(\bar{6}, 3, -1/3)$ with masses 2 TeV and 3.2×10^8 GeV respectively while the entire 24_F stays at 500 GeV. We have taken $\alpha_1(M_Z) = 0.016946 \pm 0.000006$, $\alpha_2(M_Z) = 0.033812 \pm 0.000021$ and $\alpha_3(M_Z) = 0.1184 \pm 0.0007$ and ensure that the unification takes place within the errors allowed by experimental measurements in the couplings. We find the unification scale and unified coupling to be $M_{GUT} = 6.3 \times 10^{16}$ GeV and $\alpha(M_{GUT}) = 1/18$ respectively.

In nonsupersymmetric GUTs, the dominant contribution to proton decay arises through baryon and lepton number violating gauge interactions. Such gauge bosons typically have masses of the order of the GUT scale and hence the proton life time puts a lower bound on M_{GUT} . The latest experimental limit on partial decay lifetime of proton is $\tau_p(p \rightarrow \pi^0 e^+) > 8.2 \times 10^{33}$ years [21]. This implies

$$M_{GUT} \approx (m_p^5 \alpha(M_{GUT})^2 \tau_p)^{1/4} \gtrsim 2.3 \times 10^{16} \sqrt{\alpha(M_{GUT})} \text{ GeV}, \quad (12)$$

where $m_p = 0.938$ GeV is the proton mass. The values which we obtain for M_{GUT} and $\alpha(M_{GUT})$ respect the above bounds. Further the predicted proton lifetime in this model is an order of magnitude higher than the current experimental limit and can be tested in the next generation proton decay experiments.

The color sextet fields which are introduced in order to achieve gauge coupling unification can naturally arise within SU(5) multiplets. For example $(\bar{6}, 1, -1/3)$ belongs to 45_H which is already in the model to account for realistic fermion masses while $(\bar{6}, 3, -1/3)$ can come from a super heavy 50_H multiplet. In general, the masses of all the submultiplets are of the order of M_{GUT} and one needs to assume an additional fine tuning in parameters to keep some of the components light enough to achieve unification. Such an incomplete multiplet can also arise naturally without fine tuning in orbifold grand unified theories in which the gauge symmetry is broken through boundary condition in higher space-time dimension, see for examples [22]. Note that the singlet scalar S does not interact with these color sextet scalars belonging to 45_H and 50_H at tree level as it is forbidden by the SU(5) gauge symmetry.

5. Summary and outlook

The recent observation of 750 GeV diphoton excess by the ATLAS and CMS is an intriguing result. If it persists, it would be an insurmountable evidence of new physics beyond the SM. The observed cross section for this channel also provides a hint that 750 GeV resonance cannot be the only new physics particle. We need more colored/multiply-charged particles to explain the large production cross section/diphoton branching ratio respectively. We propose a simple nonsupersymmetric SU(5) grand unified model in which extra vector-like fermions naturally arise from a 24 dimensional adjoint representation of the gauge group. They possess appropriate color and electric charges leading to successful explanation for diphoton excess. We find that the colored fermions Q_8^0 , $Q_3^{\pm 4/3}$ and $Q_3^{\pm 1/3}$ belonging to 24_F can enhance the production of singlet scalar S while the electrically charged fermions $Q_3^{\pm 4/3}$, $Q_3^{\pm 1/3}$ and L_3^\pm simultaneously enhance the $S \rightarrow \gamma\gamma$ branching ratio. We show that the observed diphoton cross section can be accounted in the model with sub-TeV adjoint fermions and with Yukawa coupling of $\mathcal{O}(1)$. For the adjoint fermion masses $M_f > 375$ GeV, a narrow width solution is preferred. A broad width scenario, as suggested by preliminary data, can be obtained if $Q_3^{\pm 1/3}$ is made lighter than 375 GeV and thereby opening the tree level decays of S . A simultaneous explanation of observed cross section and the total decay width in this case requires specific mass spectrum for adjoint fermions. The model is also shown to be consistent with the bounds on $S \rightarrow WW$, $S \rightarrow ZZ$ and $S \rightarrow Z\gamma$ decays.

The interactions of adjoint fermions with the SM fermions are forbidden using a discrete Z_2 symmetry under which 24_F is odd. Interestingly, this makes a singlet fermion residing in 24_F a candidate of cold dark matter. A successful explanation of diphoton anomaly in this model requires the mass of such dark matter particle in sub TeV range. The unification of gauge coupling is possible with light adjoint fermions and two colored sextet scalars leading to the values of unification scale and unified coupling while being consistent with the current proton lifetime limit.

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