

## Interpreting the 750 GeV diphoton excess by the singlet extension of the Manohar–Wise model postprint

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### Abstract

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### Full Text

## Preamble

#### IPMU15-0217 Interpreting the 750 GeV diphoton excess by the singlet extension of the Manohar-Wise Model

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The evidence of a new scalar particle X from the 750 GeV diphoton excess, and the absence of any other signal of new physics at the LHC so far suggest the existence of new colored scalars, which may be moderately light and thus can induce sizable  $X_{gg}$  and  $X_{\gamma\gamma}$  couplings without resorting to very strong interactions. Motivated by this speculation, we extend the Manohar-Wise model by adding one gauge singlet scalar field. The resulting theory then predicts one singlet dominated scalar  $\phi$  as well as three kinds of color-octet scalars, which can mediate through loops the  $\phi_{gg}$  and  $\phi_{\gamma\gamma}$  interactions. After fitting the model to the diphoton data at the LHC, we find that in reasonable parameter regions the excess can be explained at  $1\sigma$  level by the process  $gg \rightarrow \phi \rightarrow \gamma\gamma$ , and the

best points predict the central value of the excess rate with  $\chi^2_{\min} = 2.32$ , which corresponds to a p-value of 0.68. We also consider the constraints from various LHC Run I signals, and we conclude that, although these constraints are powerful in excluding the parameter space of the model, the best points are still experimentally allowed.

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## ## Introduction

Recently both ATLAS and CMS collaborations reported a resonance with its mass around 750 GeV in the diphoton channel [?, ?]. The local and global significances of this resonance are around  $3.6\sigma$  and  $2.3\sigma$  respectively for the ATLAS analysis, and  $2.6\sigma$  and  $2\sigma$  for the CMS analysis. Interestingly, as pointed out in [?, ?], both analyses favored the 750 GeV diphoton production rate at about 4 fb in the narrow-width approximation. Obviously, if the resonance corresponds to a new particle beyond the Standard Model (SM), its spin should be either 0 or 2. Since other searches for the WW, ZZ,  $\gamma\gamma$ , jj signals at the LHC saw no excess at the resonance, the usual spin-2 KK-graviton, which has a universal coupling to SM particles [?], should be strongly limited by the resonant dilepton searches. So in the following we focus on the spin-0 case.

Another aspect we note is that if the resonance is initiated by  $q\bar{q}$  annihilation, its production rate should be enhanced by a factor of 2.5 from naive parton distribution analysis in moving from 8 TeV LHC to 13 TeV LHC [?]. By contrast, if the resonance is initiated by gluon fusion, the enhancement factor becomes 4.7. Given that the non-observation of the resonance at the 8 TeV LHC has set an upper bound of about 2 fb on the diphoton channel, it is better to consider the gluon fusion channel as the explanation of the excess.

As shown in previous studies [?, ?], if the new scalar X only interacts with the SM particles, it cannot be fully responsible for the excess. This is because both the  $Xgg$  and  $X\gamma\gamma$  interactions are induced by loop effects, and increasing the strength of the interactions will inevitably enhance the production rates of the other SM particles, which has been tightly constrained by experimental data. So the diphoton excess implies the existence of other new particles which contribute to the interactions of X. So far additional fermions have been intensively studied to enhance the diphoton production rate, but this kind of explanation usually needs a rather strong Yukawa coupling and also a somewhat low fermion mass scale, which suffers from rather tight theoretical and experimental constraints [?]. This motivates us to consider other types of new particles which act as the mediator to enhance the  $Xgg$  and  $X\gamma\gamma$  couplings.

In this work, we take the singlet extension of the Manohar-Wise model as an

example to show that color-octet scalars are capable of doing such work. We note that although the color-octet scalars are well motivated in many basic theories, such as various SUSY constructions, topcolor models and the models with extra dimensions [?], the attempt to interpret the excess by such scalars is still absent.

Currently with insufficient experimental data, the ATLAS analysis slightly preferred a wide width of the resonance (about 45 GeV) to a narrow width [?], and by contrast the CMS analysis favored a narrow width [?]. Very recently, an analysis by combining both the ATLAS data and the CMS data was carried out, and it indicated that the narrow width was preferred [?].

This paper is organized as follows: in Sec. II, we first introduce the singlet extension of the Manohar-Wise Model, then in Sec. III we provide analytical formulae for the diphoton rate. The relevant constraints from the LHC Run I data are described in Sec. IV, and our numerical results and discussions are presented in Sec. V. For completeness, we also discuss some theoretical issues of our explanation in the subsequent section. Finally, we draw our conclusions in Sec. VII.

## ## II. The Singlet Extension of the Manohar-Wise Model

Motivated by the principle of minimal flavor violation, the Manohar-Wise model extends the SM by one family of scalars in the  $(8,2)_{1/2}$  representation of the SM gauge group  $SU(3) \times SU(2) \times U(1)$  [?]. These scalars can be written as  $S_A^R + iS_A^I$  where  $A = 1, \dots, 8$  is the color index,  $S_A^R$  and  $S_A^I$  are neutral CP-even and CP-odd ones respectively, and  $S^+$  denotes an electrically charged color-octet scalar field. In order to explain the diphoton excess, we further incorporate one real gauge singlet scalar field  $\Phi$  into the theory. Then the general renormalizable scalar potential is given by

$$\begin{aligned} V = & m_\Phi^2 \Phi^2 + \lambda_\Phi \Phi^4 + m_H^2 H^\dagger \cdot H + \lambda_H (H^\dagger \cdot H)^2 + \lambda_{H\Phi} \Phi^2 H^\dagger \cdot H \\ & + 2m_S^2 \text{Tr}(S_i^\dagger S^i) + \kappa \Phi^2 \text{Tr}(S_j^\dagger S^j) + \lambda_1 H^{\dagger i} H_i \text{Tr}(S_j^\dagger S^j) + \lambda_2 H^{\dagger i} H_j \text{Tr}(S_j^\dagger S^i) \\ & + [\lambda_3 H^{\dagger i} H^{\dagger j} \text{Tr}(S_i S_j) + \lambda_4 H^{\dagger i} \text{Tr}(S_j^\dagger S^j S_i) + \lambda_5 H^{\dagger i} \text{Tr}(S_j^\dagger S_i S^j) + \text{h.c.}] \\ & + \lambda_6 \text{Tr}(S_i^\dagger S^i S_j^\dagger S^j) + \lambda_7 \text{Tr}(S_i^\dagger S^j S_j^\dagger S^i) + \lambda_8 \text{Tr}(S_i^\dagger S^i) \text{Tr}(S_j^\dagger S^j) \\ & + \lambda_9 \text{Tr}(S_i^\dagger S^j) \text{Tr}(S_j^\dagger S^i) + \lambda_{10} \text{Tr}(S_i S_j) \text{Tr}(S^{\dagger i} S^{\dagger j}) + \lambda_{11} \text{Tr}(S_i S_j S^{\dagger j} S^{\dagger i}), \end{aligned}$$

where  $S$  is the sum of the product  $S_A^T A$  over the color index  $A$ ,  $H = (1/\sqrt{2})(0, H^0)^T$  stands for the SM Higgs field in unitary gauge,  $i, j$  are isospin indices, and the dimensionless coefficients  $\lambda_\Phi, \lambda_H, \lambda_{H\Phi}$ , and  $\lambda_\alpha$  ( $\alpha = 1, \dots, 11$ ) parameterize the interactions among the scalar fields. Note that all these coefficients except  $\lambda_4$  and  $\lambda_5$  are real parameters [?], and their magnitudes may reach 20 without conflicting with the unitarity constraint [?].

Within this theoretical framework, two CP-even color-singlet scalar particles  $\phi$  and  $h$ , and three kinds of color-octet scalar particles  $S_{A^+}$ ,  $S_{A^R}$  and  $S_{A^I}$  are predicted. In the basis  $(H^0, \Phi)$ , the squared mass matrix of the color-singlet fields is given by

$$\mathcal{M}^2 = \begin{pmatrix} m_H^2 + 3\lambda_H v^2 + \lambda_{H\Phi} f^2 & \lambda_{H\Phi} v f \\ \lambda_{H\Phi} v f & m_\Phi^2 + 12\lambda_\Phi f^2 + \lambda_{H\Phi} v^2 \end{pmatrix},$$

where  $v$  and  $f$  are the vacuum expectation values (vevs) of the fields  $H^0$  and  $\Phi$  respectively. After diagonalizing this matrix, we have

$$\begin{aligned} h &= H^0 \cos \theta + \Phi \sin \theta, \\ \phi &= -H^0 \sin \theta + \Phi \cos \theta, \end{aligned}$$

with  $\theta$  parameterizing the mixing of the fields. In our scheme for the excess,  $h$  corresponds to the SM-like Higgs boson discovered at the LHC, and  $\phi$  is responsible for the diphoton signal via the process  $gg \rightarrow \phi \rightarrow \gamma\gamma$ . So in the following, we set  $m_h = 125$  GeV,  $m_\phi = 750$  GeV and  $v = 246$  GeV, and for convenience of discussion, we choose  $f$  and  $\sin \theta$  as the input parameters of the model.

In this way, we have the following relationships:

$$\begin{aligned} \lambda_{H\Phi} &= \frac{(m_h^2 - m_\phi^2) \sin \theta \cos \theta}{v f}, \\ \lambda_H &= \frac{m_h^2 \cos^2 \theta + m_\phi^2 \sin^2 \theta - \lambda_{H\Phi} f^2}{2v^2}, \\ \lambda_\Phi &= \frac{m_h^2 \sin^2 \theta + m_\phi^2 \cos^2 \theta - \lambda_{H\Phi} v^2}{8f^2}. \end{aligned}$$

As for the color-octet particles, their masses are given by

$$\begin{aligned} m_{S^+}^2 &= m_S^2 + \kappa f^2 + \lambda_1 \frac{v^2}{2}, \\ m_{S^R}^2 &= m_S^2 + \kappa f^2 + (\lambda_1 + \lambda_2 + 2\lambda_3) \frac{v^2}{2}, \\ m_{S^I}^2 &= m_S^2 + \kappa f^2 + (\lambda_1 + \lambda_2 - 2\lambda_3) \frac{v^2}{2}, \end{aligned}$$

and the coefficients of their interactions with the color-singlet particles are given by

$$\begin{aligned} g_{hS_i^* S_i} &\equiv \tilde{Y}_i \delta^{AB} = (-\lambda_i \cos \theta + \kappa_i f \sin \theta) \delta^{AB}, \\ g_{\phi S_i^* S_i} &\equiv Y_i \delta^{AB} = (\lambda_i \sin \theta + \kappa_i f \cos \theta) \delta^{AB}, \end{aligned}$$

where  $i = +, R, I$ , and we define  $\lambda_{-+} = \lambda_1$ ,  $\lambda_{\{R,I\}} = (1/2)(\lambda_{-1} + \lambda_{-2} \pm 2\lambda_3)$ ,  $_{+} = \text{ , and } \text{ - }_R = \text{ - }_I = \text{ .$

Throughout this work, for simplicity we set  $\lambda_{\{1-11\}} = 0.1$  so that all the colored scalars are nearly degenerate (we label their common mass by  $m_{-S}$  hereafter). This assumption together with the requirements  $|\sin \theta| < 0.01$  and  $m_{-S} > 500$  GeV (see discussion below) imply that the  $h\gamma\gamma$  and  $hgg$  couplings are only slightly changed by the  $S_{-i}$ -mediated loops, which is actually favored by the 125 GeV Higgs data [?]. Note that in such a case the  $S$ ,  $T$  and  $U$  variables are scarcely changed [?]. Also note that the unbroken electric charge and color symmetries require the vevs of the colored scalars to vanish, and the vacuum stability at the scale  $m\phi = 750$  GeV requires  $m_{-S}^2 > 0$ ,  $4\lambda_{-H} \lambda_{\Phi} - \lambda_{\{H\Phi\}}^2 > 0$ . Obviously, these requirements are satisfied in our scheme.

In this work, we also assume the Yukawa couplings of the  $S_{-i}$  with quarks are negligibly small so that the  $S_{-i}$  will decay mainly through loops mediated by the colored scalars [?]. In this case,  $S_{-\{R,I\}}$  may decay into  $gg$ ,  $gZ$  and  $g\gamma$  with the  $gg$  mode being the dominant one [?]. We checked that for  $|\lambda_{-4}|, |\lambda_5|/O(0.1)$  and  $m_{-S} \sim 600$  GeV, the widths of  $S_{\{R,I\}}$  are at the order of  $10^{-3}$  MeV.

### ### III. Theoretical Prediction of the Diphoton Rate

In the extension of the Manohar-Wise model, the singlet-dominated scalar  $\phi$  can couple to vector boson pairs through its mixing with the SM Higgs field  $H^0$  or through the loop diagrams shown in Fig. 1. As a result,  $\phi$  may decay into  $\gamma\gamma$ ,  $gg$ ,  $ZZ$ ,  $WW^*$  and  $Z\gamma$ . In the following we list the partial widths of  $\phi$ , which are needed to obtain the diphoton production rate.

- The widths of  $\phi \rightarrow \gamma\gamma, gg, Z\gamma$  are given by

$$\begin{aligned} \Gamma_{\phi \rightarrow \gamma\gamma} &= \frac{G_\mu \alpha^2 m_\phi^3}{128\sqrt{2}\pi^3} \left| \sum_{i=+,R,I} N_{c,i} Q_i^2 Y_i A_0(\tau_{S_i}) - \sin \theta \times (A_1(\tau_W) + \frac{4}{3} A_{1/2}(\tau_t)) \right|^2, \\ \Gamma_{\phi \rightarrow gg} &= \frac{G_\mu \alpha_s^2 m_\phi^3}{64\sqrt{2}\pi^3} \left| \sum_{i=+,R,I} Y_i A_0(\tau_{S_i}) - \sin \theta \times A_{1/2}(\tau_t) \right|^2, \\ \Gamma_{\phi \rightarrow Z\gamma} &= \frac{G_\mu \alpha m_\phi^3}{64\sqrt{2}\pi^3} \left( 1 - \frac{m_Z^2}{m_\phi^2} \right)^3 \left| \sum_{i=+,R,I} \frac{2N_{c,i} Q_i (T_{3i} - 2Q_i \sin^2 \theta_W)}{\cos \theta_W} Y_i C_0(\tau_{S_i}^{-1}, \eta_{S_i}^{-1}) \right. \\ &\quad \left. - \sin \theta \times \left( \frac{\cos^2 \theta_W}{\sin \theta_W} C_1(\tau_W^{-1}, \eta_W^{-1}) + \frac{2(1 - \frac{8}{3} \sin^2 \theta_W)}{\sin \theta_W \cos \theta_W} A_{1/2}(\tau_t) \right) \right|^2, \end{aligned}$$

where  $A_0, A_{\{1/2\}}, C_0, C_1$  are loop functions defined in [?] with  $\tau = m\phi^2/(4m_{-}^2)$  and  $_{-} = m_{-Z}^2/(4m_{-}^2)$  ( $= W, t, S_{-i}$ ). Note that in these expressions, terms proportional to  $\sin \theta$  come from the  $H^0$ -component of  $\phi$ , which can couple directly to top quark and W boson. Also note that in the case

of a small  $\sin \theta$ , we have  $\Gamma(\phi \rightarrow \gamma\gamma) : \Gamma(\phi \rightarrow Z\gamma) : \Gamma(\phi \rightarrow gg) = 1 : 0.85 : 715$  if the colored scalars are degenerate in mass.

- The calculation of  $\Gamma(\phi \rightarrow VV)$  with  $V = W, Z$  is slightly complicated. On one side, the  $\phi WW$  and  $\phi ZZ$  couplings have tree-level contributions from the  $H^0$ -component of  $\phi$ , which are proportional to  $\sin \theta$ , and thus suppressed if  $\sin \theta = 0$ . On the other side, the couplings may get radiative corrections from the  $S_i$ -mediated loops, which might be sizable for a large  $\tan \beta$  and moderately light colored scalars. So for the sake of completeness, we calculate both contributions. In more detail, we first parameterize the effective  $\phi VV^*$  interaction as

$$\mathcal{A}_{\phi VV^*} = g_V m_V \left( A_V g_{\mu\nu} + B_V \frac{p_{1\mu} p_{2\nu}}{m_V^2} \right) \epsilon^\mu(p_1) \epsilon^{*\nu}(p_2),$$

and express the decay width of  $\phi \rightarrow VV^*$  by [?]

$$\Gamma_{\phi \rightarrow VV^*} = \delta_V \frac{G_F m_\phi^3}{64\sqrt{2}\pi^3} \left[ A_V A_V^* \lambda(m_V^2, m_V^2; m_\phi^2) + (A_V B_V^* + A_V^* B_V) \frac{\lambda(m_V^2, m_V^2; m_\phi^2)}{2} + B_V B_V^* \frac{\lambda(m_V^2, m_V^2; m_\phi^2)}{4} \right],$$

where  $\delta_V = 2(1)$  for  $V = W(Z)$  respectively and  $\lambda(x, y, z) = ((z - x - y)^2 - 4xy)/z^2$ . Then we compute the coefficients  $A_V$  and  $B_V$  up to one-loop level, which are given by

$$A_V = -\sin \theta + \frac{g^2}{16\pi^2} (C_{1V} Y_+ + Y_R + Y_I) (B_0 - 4C_{24}),$$

$$B_V = -\frac{g^2}{16\pi^2} (C_{1V} Y_+ + Y_R + Y_I) (4C_{12} + 4C_{23}).$$

In the above expressions,  $C_{1V} = 1$ ,  $\cos^2 \theta = 2\theta_W$  for  $V = W, Z$  respectively, the couplings  $Y_i$  are defined in Eq. (2.10).

- The width of  $\phi \rightarrow t\bar{t}$  is given by

$$\Gamma_{\phi \rightarrow t\bar{t}} = \sin^2 \theta \frac{3m_\phi}{8\pi} \left( \frac{m_t}{v} \right)^2 \left( 1 - \frac{4m_t^2}{m_\phi^2} \right)^{3/2}.$$

Note that since we have neglected the Yukawa couplings of the  $S_i$  with quarks, the  $\phi t\bar{t}$  interaction is solely determined by the  $H^0$ -component of  $\phi$ . As a result,  $\Gamma_{\phi \rightarrow t\bar{t}}$  as the largest one among all  $\phi \rightarrow f\bar{f}$  decays is proportional to  $\sin^2 \theta$ .

- The width of  $\phi \rightarrow hh$  is given by

$$\Gamma_{\phi \rightarrow hh} = \frac{|C_{\phi hh}|^2}{8\pi m_\phi} \sqrt{1 - \frac{4m_h^2}{m_\phi^2}},$$

where

$$C_{\phi hh} = -3\lambda_H v \sin \theta \cos^2 \theta + 12\lambda_\Phi f \sin^2 \theta \cos \theta + \lambda_{H\Phi} (-v \sin^3 \theta + f \cos^3 \theta - 2f \sin^2 \theta \cos \theta + 2v \sin \theta \cos^2 \theta) \approx -\sin \theta.$$

Note that in getting the final expression of  $C_{\phi hh}$ , we only keep the terms proportional to  $\sin \theta$ , and drop higher-order contributions in the expansion of  $\sin \theta$ .

The total width of  $\phi$  is then given by

$$\Gamma_{\text{tot}} = \Gamma_{\phi \rightarrow gg} + \Gamma_{\phi \rightarrow \gamma\gamma} + \Gamma_{\phi \rightarrow Z\gamma} + \Gamma_{\phi \rightarrow ZZ} + \Gamma_{\phi \rightarrow WW^*} + \Gamma_{\phi \rightarrow f\bar{f}} + \Gamma_{\phi \rightarrow hh} + \Gamma_{\text{new}},$$

where  $\Gamma_{\text{new}}$  represents the width for other decay modes of  $\phi$ . These modes may arise if the theory is embedded in a more complex theoretical framework.

With these formulae, the  $\phi$ -induced diphoton rate can be written as

$$\sigma_{13\text{TeV}}^{\gamma\gamma} = \frac{\Gamma_{\phi \rightarrow gg}}{\Gamma_{H \rightarrow gg}^{\text{SM}}|_{m_H=750\text{GeV}}} \times \sigma_{13\text{TeV}}^{\text{SM}}(H) \times \frac{\Gamma_{\phi \rightarrow \gamma\gamma}}{\Gamma_{\text{tot}}},$$

where  $\Gamma_{H \rightarrow gg}^{\text{SM}}$  denotes the decay width of the SM Higgs  $H$  into  $gg$  with  $m_H = 750$  GeV, and  $\sigma_{13\text{TeV}}^{\text{SM}}(H) = 735$  fb is the NNLO production rate of  $H$  at the 13 TeV LHC [?]. This expression indicates that if  $\Gamma_{\text{tot}}$  is fixed at a certain value,  $\sigma_{13\text{TeV}}^{\gamma\gamma} \propto (\Gamma_{\phi \rightarrow gg})^2$ ; and in comparison if  $\Gamma_{\text{tot}}$  is fixed at a certain value,  $\sigma_{13\text{TeV}}^{\gamma\gamma} \propto (\Gamma_{\phi \rightarrow \gamma\gamma})^4$ .

#### ## IV. Experimental Constraints

Besides the diphoton signal, our model also predicts some other signals like  $jj$ ,  $VV^*$ ,  $hh$  and  $t\bar{t}$ . Given the corresponding searches done by the ATLAS and CMS collaborations with about  $20 \text{ fb}^{-1}$  data at the LHC Run I, one can naturally ask if these signals can be used to limit our explanation. In the following, we briefly describe these searches.

- **Resonant dijet signal:** The dijet events at the 8 TeV LHC were studied in [?] and [?] by ATLAS and CMS respectively. ATLAS provided an observed 95% C.L. upper limit of 11 pb and 15 pb on the rate for a  $m = 750$  GeV Breit-Wigner resonance with  $\Gamma/m = 0.5\%$  and  $5\%$  respectively (see Fig. 9 in [?]), given that the resonance is initiated by gluon fusion. By contrast, CMS imposed a much lower upper limit, which is about 1.8 pb at 95% C.L. for a 750 GeV narrow resonance decaying into the  $gg$  final state (see Fig. 3 in [?]).

- **Resonant hh signal:** CMS searched for the resonant SM-like Higgs pair production via the four bottom quark signal, and it found that  $\sigma(\text{pp} \rightarrow X \rightarrow \text{hh} \rightarrow \text{b}\bar{\text{b}}\text{b}\bar{\text{b}}) \leq 17 \text{ fb}$  for a spin-0 resonance with  $m_X = 750 \text{ GeV}$  (see Fig. 5 in [?]). More comprehensive analyses for the resonant production were done by ATLAS, focusing on the  $\text{bb}\tau\tau$  and  $\gamma\gamma\text{WW}^*$  final states [?], the  $\gamma\gamma\text{b}\bar{\text{b}}$  final state [?] and also the  $\text{b}\bar{\text{b}}\text{b}\bar{\text{b}}$  final state [?]. Especially, the results of the  $\text{b}\bar{\text{b}}\text{b}\bar{\text{b}}$  and  $\text{bb}\tau\tau$  analyses were combined for  $m_X > 500 \text{ GeV}$ , and a 95% upper limit of 35 fb on  $\sigma(\text{gg} \rightarrow X \rightarrow \text{hh})$  was obtained for  $m_X = 750 \text{ GeV}$  (see Fig. 6 in [?]).
- **Resonant VV\* signal:** Based on up to  $5.1 \text{ fb}^{-1}$  data at the 7 TeV LHC and up to  $19.7 \text{ fb}^{-1}$  data at the 8 TeV LHC, CMS combined results from the search for a heavy Higgs boson H by  $\text{gg}$  and  $\text{qq}$  final states from  $\text{H} \rightarrow \text{WW}^*$  decay channel, and also from the search by  $\text{gg}$ ,  $\text{qq}$ ,  $\tau\tau$  and  $\text{qq}$  final states from  $\text{H} \rightarrow \text{ZZ}$  decay [?]. In either case, it obtained a 95% C.L. upper limit of about 83 fb for the cross section  $\sigma(\text{pp} \rightarrow \text{H} \rightarrow \text{VV})$  at the 8 TeV LHC with  $m_H = 750 \text{ GeV}$  (see Fig. 7 in [?]). In parallel, ATLAS performed similar studies, and it obtained the following 95% C.L. upper limits for  $m_H = 750 \text{ GeV}$ :  $\sigma(\text{gg} \rightarrow \text{H} \rightarrow \text{WW}) \leq 54 \text{ fb}$ , 37 fb in the complex-pole scheme (where the width increases with  $m_H$ ) and the narrow-width approximation respectively (see Fig. 12 and Fig. 13 in [?]), and  $\sigma(\text{gg} \rightarrow \text{H} \rightarrow \text{ZZ}) \leq 12 \text{ fb}$  (see Fig. 12 in [?]).
- **Resonant Z $\gamma$  signal:** ATLAS searched for the process  $\text{pp} \rightarrow \phi \rightarrow \text{Z}\gamma \rightarrow \bar{\ell}\ell\gamma$  [?] with  $\bar{\ell}$  denoting either e or  $\mu$ , and at the resonance  $m_\phi = 750 \text{ GeV}$ , it obtained an upper bound on the production rate at 0.24 fb when  $\phi$  is a pseudo-Goldstone boson and at 0.31 fb when  $\phi$  is a technimeson (see Fig. 3 in [?]).
- **Resonant t $\bar{t}$  signal:** CMS performed a search for the production of a heavy resonance decaying into  $t\bar{t}$  [?], and it set 95% C.L. upper limits on  $\sigma(\text{pp} \rightarrow X \rightarrow t\bar{t})$  for the resonance at 750 GeV, which were 450 fb and 550 fb for X corresponding to a vector boson Z' in the narrow width case and the wide width case ( $\Gamma/m = 10\%$ ) respectively, and 700 fb for X corresponding to a KK gluon in the Randall-Sundrum model (see Fig. 14 in [?]). ATLAS used lepton-plus-jets events to search for the  $t\bar{t}$  resonances, and it excluded the narrow spin-0 scalar resonance at 750 GeV with the production cross section greater than 700 fb (see Fig. 11 in [?]).

From the above discussion, one can get the tightest limits on various channels at the 750 GeV resonance, which are summarized in Table I. In the following, we will use these limits to select the parameter space of the model. As for the diphoton signal at the 8 TeV LHC, we note that only mild upward fluctuations at the mass window around 750 GeV were seen by ATLAS [?] and CMS [?], and they are actually consistent with the observed resonance at the 13 TeV LHC after considering the large statistical fluctuation. So to treat the diphoton signal in an unprejudiced way, we combine the diphoton data at both the 8 TeV and the 13 TeV LHC together to fit our model. In practice, we adopt the method

in [?] to do such a work. The data we take are

$$\sigma(pp \rightarrow \gamma\gamma) = \begin{cases} 0.63 \pm 0.25 \text{ fb} & \text{CMS at } \sqrt{s} = 8 \text{ TeV}, \\ 0.46 \pm 0.85 \text{ fb} & \text{ATLAS at } \sqrt{s} = 8 \text{ TeV}, \\ 5.6 \pm 2.4 \text{ fb} & \text{CMS at } \sqrt{s} = 13 \text{ TeV}, \\ 6.2_{-2.0}^{+2.4} \text{ fb} & \text{ATLAS at } \sqrt{s} = 13 \text{ TeV}, \end{cases}$$

and the  $\chi^2$  function we use is given by [?]

$$\chi^2 = \sum_{i=1}^3 \begin{cases} 2[\mu_i^{\text{exp}} - \mu_i + \mu_i \ln(\mu_i/\mu_i^{\text{exp}})] & \text{for the 13 TeV ATLAS data,} \\ \frac{(\mu_i^{\text{exp}} - \mu_i)^2}{\sigma_i^2} & \text{for the other three sets of data,} \end{cases}$$

where  $\mu_i$  is the theoretical prediction of the diphoton rate.

Besides the constraints from the different signals of  $\phi$ , the masses of the colored scalars are also constrained by the direct search for new particles at the LHC. So far the most pertinent analysis for the  $S_i$  pair production is to look for paired dijet resonances, which was performed by CMS at the 8 TeV LHC [?]. This analysis concentrated on the process  $gg \rightarrow CC \rightarrow (jj)(jj)$  with C denoting a color-octet vector boson called coloron [?], and it set the upper bounds on the cross section of the paired dijet events as a function of the coloron mass, which were presented in Fig. 7 of [?]. In order to apply this analysis to our work, we first assume that the processes  $gg \rightarrow S_R S_R, S_I S_I \rightarrow 4j$  have the same cut efficiencies as those of the coloron pair production process in the analysis, then we calculate the  $S_i$  production rates at tree level to compare with Fig. 7 in [?]. We conclude that  $m_S = 450$  GeV cannot be excluded. We also note that the colored scalars may form bound states  $O_R^0, O_I^0, O_+^0, O_L^0$ , which were collectively called octetonia in [?]. The masses of these bound states are around  $2m_S$  and they can be produced directly at the LHC to generate various signals such as  $gg \rightarrow O_R^0, O_I^0, O_+^0, O_L^0 \rightarrow gg, WW^*, ZZ, \gamma\gamma, Z\gamma$  [?]. In order to determine the mass bound imposed by the octetonia production, we calculate the rates of the signals at the 8 TeV LHC by the formula presented in the appendix of [?], and compare them with the corresponding LHC bounds introduced in this section. We find that due to their relatively low production rates, the octetonia as light as 750 GeV are still experimentally allowed. So in summary, it is fair to say that the colored scalars heavier than about 500 GeV are still compatible with the LHC data.

## ## V. Numerical Results and Discussions

In order to answer whether the extended Manohar-Wise model can explain the diphoton data collected at the LHC after considering the constraints described in Sec. IV, we fix  $f = 1$  TeV and  $m_S = 600$  GeV (with  $m_S = 1$  TeV as an alternative choice), and scan the following parameter space of the model:

$$0 < \kappa \leq 10, \quad |\sin \theta| \leq 0.05.$$

For each parameter point encountered in the scan, we first check whether it survives the constraints listed in Table I, then for the surviving point we perform a fit to the diphoton data.

[Figure 2: see original paper]

Our results are shown in Fig. 2 on the  $\sigma_{13\text{TeV}} - \Gamma_{\text{tot}}$  planes (left panels) and  $\sigma_{13\text{TeV}} - \sin \theta$  planes (right panels) with the upper panels being for the  $m_S = 600$  GeV case and the lower panels for the  $m_S = 1$  TeV case. The regions filled by colors from gray to deep blue represent the parameter space that survives the constraints and meanwhile is able to explain the diphoton data at  $3\sigma$ ,  $2\sigma$  and  $1\sigma$  levels respectively. In comparison, the regions covered by straw color are excluded by the constraints presented in Table I. The boundary lines for some constraints in Table I are also plotted with the right or upper side of the curves being excluded for the left panels, and the upper or outboard side of the curves being excluded for the right panels. The green lines represent the parameter points which can predict the central value of the diphoton excess (about 3.9 fb in our fit). For these points, they predict  $\chi^2_{\text{min}} = 2.32$ , which corresponds to a p-value of 0.68.

From Fig. 2, one can learn the following facts:

- The singlet extension of the Manohar-Wise model can interpret the 750 GeV diphoton excess at  $1\sigma$  level without conflicting with any constraints from the LHC Run I, and the corresponding parameter space is characterized by  $|\sin \theta| < 0.01$  and  $f > 1$  TeV. In Table II, we list the detailed information for two of the best points in our fits with one corresponding to the  $m_S = 600$  GeV case and the other corresponding to the  $m_S = 1$  TeV case.
- For the degenerate colored scalars, the choice of their masses does not influence the fit quality. This is obvious by comparing the left upper panel with the left lower panel. In fact, if a moderately higher value of  $m_S$  is adopted, one can always choose a larger  $f$  to keep  $\Gamma_{\phi \rightarrow gg}$  and  $\Gamma_{\phi \rightarrow \gamma\gamma}$  roughly unchanged (see the formulae in Section III). This feature has been reflected in Table II for the two best points.
- Since  $\sin \theta$  is small in order to satisfy the constraints in Table I,  $\phi \rightarrow gg$  is always the dominant decay mode, and consequently the total width of  $\phi$  is less than about 0.2 GeV. We point out that, if the theory is embedded in a more complex framework, in principle  $\phi$  may decay dominantly into other particles such as the dark matter candidate and/or multi-jets so that its width can be enhanced greatly. Considering  $\sigma_{13\text{TeV}} \propto (f)^4 / \Gamma_{\text{tot}}$ , one can infer that if  $\Gamma_{\text{tot}}$  is enlarged by a factor of 100,  $f$  has to be enhanced by roughly 3.2 times to keep  $\sigma_{13\text{TeV}}$  unchanged. This situation is acceptable if the colored scalars are moderately light (so that

f can be relatively small). So our explanation for the excess is still viable even for a significantly wider width of  $\phi$ .

- The signal channels listed in Table I, especially the hh and ZZ channels, have tightly limited the parameter space of the model to explain the diphoton excess. For example, the resonant hh signal requires  $\sin \theta < 0.01$ , and the dijet signal imposes an upper bound on  $f$ .

[TABLE:II]

### ## VI. Other Aspects of Our Explanation

From the discussions in the above section, one can learn that our explanation of the diphoton excess is featured by a moderately large  $\lambda$  for a fixed  $f$ . In this case, the evolutions of  $\lambda$ ,  $\lambda_{\Phi}$  and  $\lambda\{H\Phi\}$  with the energy scale by the renormalization group equation (RGE) can change greatly their values at the scale  $m_{\phi} = 750$  GeV, which is obvious from the  $\beta$  functions of the coupling coefficients listed in the appendix. As a result, the vacuum may become unstable, and/or the theory may become non-perturbative when the energy scale surpasses a critical value. In the following, we address these issues.

For large field values  $H^0, \Phi \gg v, f$ , the potential of the color-singlet scalars is very well approximated by its RG-improved tree-level expression [?],

$$V_{\text{tree}}^{\text{eff}} \approx \lambda_{\Phi}(\mu)\Phi^4 + \lambda_H(\mu)(H^0)^4 + \lambda_{H\Phi}(\mu)\Phi^2(H^0)^2,$$

where  $\mu$  is the scale of the RGE, and it satisfies  $\mu \approx m_{\phi}, f$  in our interested case. Then the condition of the absolute stability of the potential is given by

$$4\lambda_H(\mu)\lambda_{\Phi}(\mu) - \lambda_{H\Phi}^2(\mu) > 0.$$

In order to check whether this condition is satisfied, we show in the left panel of Fig. 3 the dependence of  $\lambda_{\Phi}$ ,  $\lambda_H$  and  $\lambda\{H\Phi\}$  on the energy scale for the first benchmark point in Table II. This panel indicates that, due to the push-up of the  $\lambda^2$  term in the  $\beta\{\lambda_{\Phi}\}$  function,  $\lambda_{\Phi}$  increases rapidly with  $\mu$ , and consequently the stability condition is always satisfied. But on the other hand, we note from the panel that  $\lambda_{\Phi}$  will reach its Landau pole at  $\mu \approx 2 \times 10^8$  GeV. Considering that the  $\beta$  function also contains the  $\lambda^2$  term, we imagine that  $\lambda_H$  should also have such a behavior. The evolution of  $\lambda_H$  with the RGE scale is presented in the right panel of Fig. 3 for different choices of  $\lambda$ . Here  $\lambda = \{750\text{GeV}\} = 1.3$  corresponds to the first benchmark point in Table II, and  $\lambda = \{750\text{GeV}\} = 0.8, 1.6$  are the boundary values of  $\lambda$  to explain the diphoton excess at  $2\sigma$  level if  $\sin \theta, m_S$  and  $f$  take the same values as the benchmark point. This panel indicates that, for the parameter region considered to explain the excess, our theory keeps perturbative until the scale at about  $10^7$  GeV. Given that this scale is much higher than the electroweak scale, we think that our explanation of the excess is acceptable.

Before we end the discussion, we emphasize that the diphoton excess actually imposes constraints on the product  $f$ . So if one chooses a larger value of  $f$ , a lower value of  $\lambda$  is still capable of explaining the excess. This will postpone the appearance of the Landau poles. For example, if  $f = 1$  TeV for the first point in Table II is switched to  $f = 2$  TeV so that  $\lambda$  is decreased by one half, we checked that the Landau pole will appear at about  $2 \times 10^9$  GeV, which is about one order higher than the  $f = 1$  TeV case.

## ## VII. Conclusion

The evidence of a new scalar particle  $X$  from the 750 GeV diphoton excess, and the absence of any other signal of new physics at the LHC so far suggest the existence of new colored scalars, which may be moderately light and thus can induce sizable  $Xgg$  and  $X\gamma\gamma$  couplings without resorting to very strong interactions. Motivated by this speculation, we extended the Manohar-Wise model by adding one gauge singlet scalar field. The resulting theory then predicts one singlet-dominated scalar  $\phi$  as well as three kinds of colored scalars, which can mediate through loops the  $\phi gg$  and  $\phi\gamma\gamma$  interactions. Within this theoretical framework, we investigated whether the diphoton excess can be explained by the process  $gg \rightarrow \phi \rightarrow \gamma\gamma$ . For this purpose, we scanned the parameter space of the model by considering the constraints from various LHC Run I signals, and for each surviving sample, we performed a fit to the 750 GeV diphoton data collected at both the 8 TeV and the 13 TeV LHC. It turns out that in reasonable parameter regions of the model, the diphoton excess can be explained at  $1\sigma$  level without conflicting with any experimental constraints. The best points in the fit can predict the central value of the excess with  $\chi^2_{\min} = 2.32$ , which corresponds to a p-value of 0.68.

## ## Appendix A: $\beta$ functions for various coupling coefficients

In this appendix, we investigate the  $\beta$  functions of different coupling coefficients in the singlet extended Manohar-Wise model. Compared with the original version of the model, the extended theory introduces new operators such as  $\Phi^4$ ,  $\Phi^2|H|^2$  and  $\Phi^2\text{Tr}(S^\dagger_j S_j)$ . As a result, some  $\beta$  functions for  $\lambda_i$  get additional contributions, and meanwhile new  $\beta$  functions corresponding to the operators appear. In this work, we get the expressions of these functions by the technique in [?], and verify them by comparing parts of our results with their corresponding ones in [?] where the  $\beta$  functions for  $\lambda_i$  were obtained in the Manohar-Wise model and also with those in [?] where all  $\beta$  functions in the singlet extension of the SM were given. In the following, we only list the  $\beta$  functions that are affected by  $\lambda$ ,  $\lambda\{H\Phi\}$  and  $\lambda_\Phi$ , which are given by

$$\begin{aligned}
(16\pi^2)\beta_\kappa &= 4\kappa^2 + 24\kappa\lambda_\Phi + 17\kappa\lambda_8 + 4\lambda_1\lambda_{H\Phi} + 2\lambda_2\lambda_{H\Phi} - (18g_3^2 + 9g_2^2 + 9g_1^2)\kappa, \\
(16\pi^2)\beta_{\lambda_H} &= 24\lambda_H^2 + 4\lambda_{H\Phi}^2 + 4\lambda_1^2 + 2\lambda_2^2 + 4\lambda_1\lambda_2 + 4|\lambda_3|^2 - (9g_2^2 + 9g_1^2)\lambda_H + 12y_t^2\lambda_H - 6y_t^4, \\
(16\pi^2)\beta_{\lambda_\Phi} &= 72\lambda_\Phi^2 + 4\lambda_{H\Phi}^2 + 2\kappa^2, \\
(16\pi^2)\beta_{\lambda_{H\Phi}} &= 8\lambda_{H\Phi}^2 + 12\lambda_{H\Phi}\lambda_H + 24\lambda_{H\Phi}\lambda_\Phi + 8\kappa\lambda_1 + 4\kappa\lambda_2 - (9g_2^2 + 9g_1^2)\lambda_{H\Phi} + 6y_t^2\lambda_{H\Phi}, \\
(16\pi^2)\beta_{\lambda_1} &= 2\lambda_1^2 + 17\lambda_1\lambda_8 + 12\lambda_1\lambda_H + 4\lambda_2\lambda_H + 4\kappa\lambda_{H\Phi} - (18g_3^2 + 9g_2^2 + 9g_1^2)\lambda_1 + 6y_t^2\lambda_1 + 6\left(\frac{4}{3}g_3^2 + \frac{9}{4}g_2^2 + \frac{1}{3}g_1^2\right), \\
(16\pi^2)\beta_{\lambda_8} &= 20\lambda_8^2 + 2\kappa^2 - (36g_3^2 + 9g_2^2 + 9g_1^2)\lambda_8 + 6y_t^2\lambda_8 + \beta'_8,
\end{aligned}$$

where  $(16\pi^2)\beta\{g_{-i}\} = b_{-i}g_{-i}^3$  with  $(b_1, b_2, b_3) = (41/10, -19/6, -7)$  in the SM, and  $(49/10, -11/6, -5)$  after considering the effect of the colored scalars, and  $(16\pi^2)\beta\{y_{-t}\} = y_{-t}(9y_{-t}^2/2 - 8g_3^2 - 9g_2^2/4 - 17g_1^2/20)$ , and  $\beta'_{1-8}$  denote the effects from the couplings  $\lambda\{2-7\}$  and  $\lambda\{9-11\}$  with their lengthy expressions presented in [?]. Note that in getting these expressions, we have used the standard normalization  $g_1^2 = (5/3)g^2$ . Also note that these  $\beta$  functions are valid only at the energy scale where the colored scalars are active.

Finally, we remind that the expressions of the  $\beta$  functions not listed here, which are for  $\lambda\{2-7\}$  and  $\lambda\{9-11\}$ , were given in the appendix of [?]. These functions are not important for our calculation since they are unaffected directly by the large coefficient  $\beta$ , and meanwhile the initial values of  $\lambda\{1-11\}$  at the scale  $m\phi = 750$  GeV are set to be very small. In fact, we checked that the effects of  $\lambda\{2-7\}$  and  $\lambda\{9-11\}$  on the running of  $\beta$ ,  $\lambda_\Phi$ ,  $\lambda\{H\Phi\}$ ,  $\lambda_H$ ,  $\lambda_1$  and  $\lambda_8$  are negligibly small.

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