The 750 GeV diphoton resonance in the light of a 2HDM with S_3 flavour symmetry

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Very recently we proposed a predictive 2 Higgs Doublet Model with S_3 flavour symmetry that successfully accounts for fermion masses and mixings. In this letter, motivated by the 750 GeV Higgs diphoton resonance recently reported by the ATLAS and CMS collaborations, we modify this model by adding exotic top partners with electric charge $\frac{5}{3}$. This simple modification enables our model to successfully account for the Higgs diphoton excess at 750 GeV provided that the exotic quark masses are in the range $[1, 1.8]$ TeV, for $O(1)$ exotic quark Yukawa couplings.

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Introduction.

Recently, the ATLAS and CMS collaborations reported an excess of events above the expected background in the diphoton final state. This is very promising as both collaborations have the excess at an invariant mass of about 750 GeV, and with local statistical significance of $3.9\,\sigma$ (ATLAS) and $2.6\,\sigma$ (CMS). The confirmation of this excess would constitute proof of physics beyond the Standard Model (SM). Although the excess may turn out to be a statistical fluctuation, it is very enticing to consider models that include in their field content something that can account for a resonance at 750 GeV and thus accounts for the excess of events.

This diphoton final state excess has generated much activity in the community. Many works have considered the excess of events in a model independent way, see [2–12]. Another study considered the implications of the Higgs diphoton resonance for the stability of the Higgs, naturalness and inflation [13].

Previous works have studied the resonant production at the LHC of (pseudo-) scalars coupled to two photons and gluons in the mass region from 30 GeV to 2 TeV [14], and of the observable effects of new scalar particles [15].

A myriad of explanations have been considered since the announcement of the excess. Adding scalar singlets is a fairly straightforward option, see [16–20], and [21](which explores several scenarios including a scalar singlet). The scalar singlet model can be further extended with extra dimensions [22], or, alternatively, with additional vector leptoquarks, which also allow to simultaneously explain the B decay anomalies [23].

Supersymmetric explanations are possible and the excess has been interpreted in the context of the Minimimal Supersymmetric Standard Model (MSSM) [24] and its R-symmetry violating version [25].

Extending the SM gauge symmetry can also explain the excess, as described by [26–36], and models based on strongly coupled theories were considered by [2, 3, 37–44]. An extended broken symmetry with an extra Higgs boson and massive vector bosons can account for the diboson anomaly and the anomalous $t\bar{t}$ forward-backward asymmetry [45]

Models with extra fermions [46], in particular vector-like fermions had been considered before [47–50] and after the announcement [2, 3, 5, 8, 51–58], and other works relate the diphoton excess with loop TeV-scale seesaw mechanisms, either at two [59] or three loops [60].

Relating the excess with dark matter has been extensively considered, see [39, 61–71].

There are also sgoldstino [72–74], radion [75, 76] and exotic heavy axion [37, 38, 77] interpretations of the 750 GeV excess.

String-motivated models were considered in [78–80].

Finally, a rather natural and popular framework to explain the excess is that of 2 Higgs Doublet Models (2HDMs), which have been considered in [51, 81–86] and will also be considered in this letter, where we consider a simple modification of an existing 2HDM, [87] by adding exotic top quark partners.

The model. We consider the 2HDM that we recently proposed in [87], with the SM gauge symmetry supplemented by the $S_3 \otimes Z_3 \otimes Z_3' \otimes Z_{14}$ discrete group. The scalar sector has two Higgs doublets (assigned as trivial S_3 singlets) plus four SM singlet scalars assigned as one S_3 trivial singlet (χ), one S_3 non-trivial singlet (ζ) and one S_3 doublet (ξ). In order to successfully explain the LHC diphoton excess at 750 GeV, we extend the fermion sector of our 2HDM by including four $SU(2)_L$ singlet exotic quark fields with electric charge $\frac{5}{3}$, T_{1L}, T_{1R}, T_{2L}, T_{2R}, grouped into two S_3 doublets, i.e., $T_L = (T_{1L}, T_{2L})$, $T_R = (T_{1R}, T_{2R})$. These exotic quarks fields are neutral under the $Z_3 \otimes Z_3'$ discrete symmetry but charged under the Z_{14} symmetry as:

$$T_L \to e^{-\frac{\pi i}{7}} T_L, \qquad T_R \to T_R. \tag{1}$$

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The remaining particles have the $S_3 \otimes Z_3 \otimes Z_3' \otimes Z_{14}$ discrete symmetry charge assignments described in [87].

In this model, the S_3 symmetry reduces the number of parameters in the Yukawa sector making this 2HDM more predictive, and the remaining symmetries control the allowed Lagrangian terms by distinguishing the fields. For example, the two scalar $SU(2)_L$ doublets have different Z_3 charges (ϕ_1 being neutral). The Z_3' and Z_{14} symmetries shape the hierarchical structure of the fermion mass matrices necessary to get a realistic pattern of fermion masses and mixing. The assignments of the scalar and fermion particles particles are given in [87], giving rise to the following Yukawa terms for the quark and lepton sectors:

$$\begin{aligned}
\mathcal{L}_Y^q &= \varepsilon_{33}^{(u)}\overline{q}_{3L}\widetilde{\phi}_1 u_{3R} + \varepsilon_{23}^{(u)}\overline{q}_{2L}\widetilde{\phi}_2 u_{3R}\frac{\chi^2}{\Lambda^2} + \varepsilon_{13}^{(u)}\overline{q}_{1L}\widetilde{\phi}_2 u_{3R}\frac{\chi^3}{\Lambda^3} \\
&+\varepsilon_{22}^{(u)}\overline{q}_{2L}\widetilde{\phi}_1 U_R\frac{\xi\chi^3}{\Lambda^4} + \varepsilon_{11}^{(u)}\overline{q}_{1L}\widetilde{\phi}_1 U_R\frac{\xi\chi^4\zeta^3}{\Lambda^8} \\
&+\varepsilon_{33}^{(d)}\overline{q}_{3L}\phi_1 d_{3R}\frac{\chi^3}{\Lambda^3} + \varepsilon_{22}^{(d)}\overline{q}_{2L}\phi_2 d_{2R}\frac{\chi^5}{\Lambda^5} \\
&+\varepsilon_{12}^{(d)}\overline{q}_{1L}\phi_2 d_{2R}\frac{\chi^6}{\Lambda^6} + \varepsilon_{21}^{(d)}\overline{q}_{2L}\phi_2 d_{1R}\frac{\chi^6}{\Lambda^6} \\
&+\varepsilon_{11}^{(d)}\overline{q}_{1L}\phi_2 d_{1R}\frac{\chi^7}{\Lambda^7} + y_T\overline{T}_L T_R\chi \qquad (2)
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_Y^l &= \varepsilon_{33}^{(l)}\overline{l}_{3L}\phi_1 l_{3R}\frac{\chi^3}{\Lambda^3} + \varepsilon_{23}^{(l)}\overline{l}_{2L}\phi_1 l_{3R}\frac{\chi^3}{\Lambda^3} + \varepsilon_{22}^{(l)}\overline{l}_{2L}\phi_1 l_{2R}\frac{\chi^5}{\Lambda^5} \\
&+\varepsilon_{32}^{(l)}\overline{l}_{3L}\phi_1 l_{2R}\frac{\chi^5}{\Lambda^5} + \varepsilon_{11}^{(l)}\overline{l}_{1L}\phi_2 l_{1R}\frac{\chi^7\zeta}{\Lambda^8} \\
&+\varepsilon_{11}^{(\nu)}\overline{l}_{1L}\widetilde{\phi}_2\nu_{1R}\frac{\chi^3}{\Lambda^3} + \varepsilon_{12}^{(\nu)}\overline{l}_{1L}\widetilde{\phi}_2\nu_{2R}\frac{\chi^3}{\Lambda^3} \\
&+\varepsilon_{21}^{(\nu)}\overline{l}_{2L}\widetilde{\phi}_1\nu_{1R} + \varepsilon_{22}^{(\nu)}\overline{l}_{2L}\widetilde{\phi}_1\nu_{2R} + \varepsilon_{31}^{(\nu)}\overline{l}_{3L}\widetilde{\phi}_1\nu_{1R} \\
&+\varepsilon_{32}^{(\nu)}\overline{l}_{3L}\widetilde{\phi}_1\nu_{2R} + M_1\overline{\nu}_{1R}\nu_{1R}^c + M_2\overline{\nu}_{2R}\nu_{2R}^c \\
&+M_{12}\overline{\nu}_{1R}\nu_{2R}^c + h.c. \qquad (3)
\end{aligned}$$

As the quark masses are related with the quark mixing parameters, we set the VEVs of the SM singlet scalars with respect to the Wolfenstein parameter $\lambda = 0.225$ and the new physics scale Λ:

$$v_\xi \sim v_\zeta \sim v_\chi = \lambda\Lambda. \qquad (4)$$

From the Yukawa terms given above and considering that the VEV of ξ is aligned as $(1,0)$ in the S_3 direction [87], we find that quark, charged lepton and light active neutrino mass matrices are:

$$\begin{aligned}
M_U &= \frac{v}{\sqrt{2}}\begin{pmatrix} c_1\lambda^8 & 0 & a_1\lambda^3 \\ 0 & b_1\lambda^4 & a_2\lambda^2 \\ 0 & 0 & a_3 \end{pmatrix}, \\
M_D &= \frac{v}{\sqrt{2}}\begin{pmatrix} e_1\lambda^7 & f_1\lambda^6 & 0 \\ e_2\lambda^6 & f_2\lambda^5 & 0 \\ 0 & 0 & g_1\lambda^3 \end{pmatrix}, \qquad (5)
\end{aligned}$$

$$\begin{aligned}
M_l &= \frac{v}{\sqrt{2}}\begin{pmatrix} x_1\lambda^8 & 0 & 0 \\ 0 & y_1\lambda^5 & z_1\lambda^3 \\ 0 & y_2\lambda^5 & z_2\lambda^3 \end{pmatrix}, \qquad (6) \\
M_\nu &= \begin{pmatrix} W^2 & \kappa WX & WY \\ \kappa WX & X^2 & \kappa XY \\ WY & \kappa XY & Y^2 \end{pmatrix}, \qquad \kappa = \cos\varphi.
\end{aligned}$$

where $v = 246$ GeV and a_k $(k = 1, 2, 3)$, b_1, c_1, g_1, f_1, f_2, e_1 e_2, x_1, y_1, y_2, z_1, z_2 and κ are $\mathcal{O}(1)$ parameters, whereas X, Y and W are parameters with dimension $\sqrt{m}$ where m has mass dimension. The Cabbibo mixing arises from the down-type quark sector whereas the up-type quark sector contributes to the remaining mixing angles [88]. Furthermore, light active neutrino masses arise via type I seesaw mechanism with two heavy right handed Majorana neutrinos ν_{1R} and ν_{2R}. We have shown in [87] that the fermion mass textures given above are consistent wih the current data on SM fermion masses and mixings.

The 750 GeV scalar resonance. The recently reported excess in the diphoton final state can be attributed to the Z_{14} breaking scalar χ, which, taking into account the heavy exotic fermions, is predominantly produced via gluon fusion through the triangular loop diagrams with T_1 and T_2. The corresponding total cross section σ is a function of the gluon production rate $\Gamma(gg \to \chi)$ and the consequent decay rate into photons $\Gamma(\chi \to \gamma\gamma)$

$$\Gamma(gg \to \chi) = K^{gg}\frac{\alpha_s^2 m_\chi^3}{64\pi^3 v_\chi^2}\Big|F(x_T)\Big|^2, \qquad (7)$$

$$\Gamma(\chi \to \gamma\gamma) = \frac{\alpha^2 m_\chi^3}{64\pi^3 v_\chi^2}\Big|N_c Q_T^2 F(x_T)\Big|^2, \qquad (8)$$

where $m_\chi \simeq 750\,\text{GeV}$ denotes the resonance mass, $x_T \equiv 4m_T^2/m_\chi^2$, and $K^{gg} \sim 1.5$ accounts for higher order QCD corrections. F(x) is a loop function given by

$$F(x) = 2\,x\big(1 + (1-x)f(x)\big),\; f(x) = \big(\arcsin\sqrt{1/x}\big)^2.$$

The latter is valid only for $x_T > 1 \Leftrightarrow 4m_T > m_\chi$ implying that the S_3 breaking scale be higher or around the Z_{14} breaking scale to ensure this condition is fulfilled without further need of finetuning. Finally, we obtain

$$\sigma = \frac{\pi^2}{8}\frac{\Gamma(\chi \to \gamma\gamma)\frac{1}{s}\int_{m_\chi^2/s}^1 \frac{dx}{x} f_g(x) f_g\left(\frac{m_\chi^2}{sx}\right)\Gamma(gg \to \chi)}{m_\chi\Gamma_\chi}$$

with $\sqrt{s} = 13\,\text{TeV}$ being the LHC center of mass energy, Γ_χ the total decay width of χ and $f_g(x)$ the gluon distribution function. To obtain a rough estimate of σ we assume for simplicity unified and natural Yukawa couplings of the exotic quarks $y_{T_i} \sim 1$, which with $v_\chi \approx 1.2\,\text{TeV}$ amounts to $\sigma \approx 7\,\text{fb}$. This is well within the limits given by the ATLAS and CMS experiments [2]

$$\sigma_{\text{ATLAS}} = 10 \pm 3\,\text{fb}\,, \quad \sigma_{\text{CMS}} = 6 \pm 3\,\text{fb}\,.$$

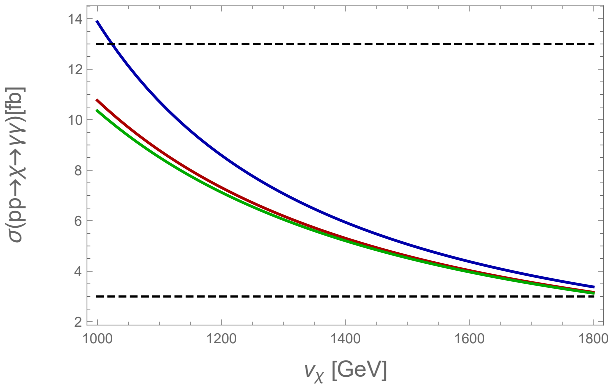

FIG. 1: Total cross section $\sigma(pp \to \chi \to \gamma\gamma)$ as a function of v_χ for and different values of the exotic quark Yukawa couplings 1.5, 1 and 0.5 (in the curves from top to bottom, respectively), assuming $\sqrt{s} = 13\,TeV$ and $\alpha_s(m_\chi/2) \simeq 0.1$. The horizontal lines denote the experimentally allowed limits of the diphoton signal given by ATLAS and CMS, which amount to $10 \pm 3 fb$ and $6 \pm 3\,fb$, respectively. The limits require $v_\chi \lesssim 1.8\,$TeV if natural order one exotic quark Yukawa couplings are assumed.

We expect the heavy exotic quark masses to reside in the vicinity of χ at around 1.2 TeV, which provides a rich phenomenology for LHC run 2 that, therefore, can test not only the 750 GeV diphoton resonance, but also the origin of fermion masses and mixings.

The total cross section was computed using the MSTW2008 next-to-leading-order gluon distribution functions [89] as a function of v_χ for different values of the exotic quark Yukawa couplings. As shown in Fig. 1 the cross section depends crucially on the VEV v_χ more so than on the Yukawa couplings, which, however, if sizable can also enhance σ significantly in particular for lower v_χ values.

If we further require that σ be within the experimental limits given by ATLAS and CMS, we predict v_χ to be smaller than 1.8 TeV, which on the one hand sets the Z_{14} breaking scale and on the other hand fixed the expected particle masses of χ and the exotic quarks T_i to be in the same region.

Conclusion. The same flavon that is responsible for the shaping of the fermion mass and mixing matrices can explain the recently reported 750 GeV excess in the diphoton channel. This is shown using a predictive flavor model based on the $S_3 \otimes Z_3 \otimes Z_3' \otimes Z_{14}$ symmetry with the addition of heavy exotic fermions with the electric charge $\frac{5}{3}$. Attributing the Z_{14} breaking scalar to the resonance allows one to fix the energy of the breaking scale and, hence, enables immediate testing of the model at the current LHC run.

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