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Diphoton decay for a 750 GeV scalar boson in a $SU(6) \otimes U(1)_X$ model

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Abstract

We propose a new $SU(6) \otimes U(1)_X$ GUT model free from anomalies, with a 750 GeV scalar candidate which can decay into two photons, compatible with the recent diphoton signal reported by ATLAS and CMS collaborations. This model gives masses to all fermions and may explain the 750 GeV signal through one loop decays to $\gamma\gamma$ with charged vector and charged Higgs bosons, as well as up- and electron-like exotic particles that arise naturally from the condition of cancellation of anomalies of the $SU(6) \otimes U(1)_X$ group. We obtain, for different width approximations, allowed mass regions from 900 GeV to 3 TeV for the exotic up-like quark, in agreement with ATLAS and CMS collaborations data.

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1. Introduction

Recently the ATLAS and CMS collaborations reported a diphoton signal excess with invariant mass of 750 GeV [1,2] which has been the subject of many interpretations in the literature using different extensions of the standard model (SM) [3–11]. In this work, we consider the $SU(6) \otimes U(1)_X$ extension proposed in [13] in the framework of the flipped $SU(6)$ models [12] as a feasible model that may explain the diphoton excess. These kinds of flipped models have

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very interesting features. First, by requiring a high breaking scale ($\sim 10^{17}$ GeV) for the flipped $SU(6)$ and its $SU(5)$ subgroup [14] the proton decay problem can be avoided. Second, they are able to solve the doublet-triplet splitting problem through the pseudo-Goldstone mechanism as in $SU(6)$ [15,16] and $[SU(3)]^3$ [17]. Also, they provide unification of gauge couplings as in the flipped $SU(5)$ model [18,19]. Finally, these models may develop see-saw masses compatible with the phenomenological active neutrinos [20,21] if one singlet heavy state is introduced.

The $SU(6) \otimes U(1)_X$ extension considered here contains the $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$ model (hereafter 331 model) [22–25] as a subgroup that allows us to address the observed diphoton excess through new exotic charged Higgs bosons into the loop at the TeV scale. In the flipped model, the $U(1)_X$ symmetry changes the exotic down type quark (charge $-1/3$) by an up type quark (charge $2/3$) in the multiplets, which increases the coupling with photons and gluons into the loop, resulting in a significantly enhanced $pp \rightarrow \gamma\gamma$ cross section, compatible with the reported data.

The 331 model can be embedded into the grand unified group $SU(6) \otimes U(1)_X$ with the following spontaneous symmetry breaking (SSB) chain:

$$\begin{aligned}
 SU(6) \otimes U(1)_X &\xrightarrow{\Phi} SU(3)_C \otimes SU(3)_L \otimes U(1)_X \xrightarrow{H_1, H_S} \\
 &SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \xrightarrow{H_2, H_3, H_S} SU(3)_C \otimes U(1)_Q
 \end{aligned}
 \tag{1}$$

which is mediated by the five Higgs fields Φ , H_1 , H_2 , H_3 and H_S in the $\mathbf{35}$, $\bar{\mathbf{6}}$, $\bar{\mathbf{6}}$, $\bar{\mathbf{15}}$ and $\bar{\mathbf{15}}$ representations, respectively. From the mixing of the real components of the fields H_1 and H_S we will obtain two real scalar fields, our candidate for the 750 GeV signal (ξ), and the other at the TeV scale (ξ').

This paper is organized as follows. In section 2, we show the particle content of a $SU(6) \otimes U(1)_X$ model as an anomaly free theory which contains the 331, 321 and 31 subgroups and their SSB scheme. We describe the Yukawa Lagrangian showing that four Higgs fields are sufficient to give masses to all fermions. We also show the most general Higgs potential terms compatible with the symmetries and identify the relevant quartic couplings that will induce the process $pp \rightarrow \xi \rightarrow \gamma\gamma$. Section 3 is devoted to explore allowed regions consistent with the reported cross section of the 750 GeV signal. Finally, in section 4, we summarize our conclusions.

2. $SU(6) \otimes U(1)_X$ model

$SU(6) \otimes U(1)_X$ strong-electroweak models provide us with a new framework which contains 331 and SM models for one family of fermions as effective low energy field theories. In order to include the three families we consider replicas of the first family as in the SM. Below, we describe some remarkable properties of these models.

- The cancellation of the $[SU(6)]^3$, $[SU(6)]^2U(1)_X$, $[\text{Grav}]^2U(1)_X$ and $[U(1)_X]^3$ chiral anomaly equations, shown in reference [13], provides us with a set of multiplets with non-trivial $U(1)_X$ charges which are family independent. We require two sextets $\bar{\mathbf{6}}$, one anti-symmetric $\mathbf{15}$ multiplet and three singlets with charges $X_{\bar{\mathbf{6}}} = -2/3$, $X_{\mathbf{15}} = 1/3$ and $X_{\mathbf{1}} = 1$, respectively.
- The symmetry breaking $SU(6) \rightarrow SU(3)_C \otimes SU(3)_L \otimes U(1)_Y$ gives us the following branching rules:

$$\bar{\mathbf{6}} = (\bar{\mathbf{3}}_C \otimes \mathbf{1}_L)_{1/3} \oplus (\mathbf{1}_C \otimes \mathbf{3}_L)_{-1/3},
 \tag{2}$$

$$\mathbf{15} = (\bar{\mathbf{3}}_C \otimes \mathbf{1}_L)_{2/3} \oplus (\mathbf{1}_L \otimes \mathbf{3}_L)_{-2/3} \oplus (\mathbf{3}_C \otimes \bar{\mathbf{3}}_L)_0, \tag{3}$$

where $(\mathbf{n} \otimes \mathbf{m})_{Y'}$ are tensorial products of \mathbf{n} $SU(3)_C$ multiplet with \mathbf{m} $SU(3)_L$ multiplets and Y' corresponds to the $U(1)_{Y'}$ quantum number normalized as $2Y'/\sqrt{3}$, where:

$$Y' = \frac{1}{2\sqrt{3}} \text{diag} (+1 \quad +1 \quad +1 \quad -1 \quad -1 \quad -1). \tag{4}$$

This gives us the following multiplets for the first family:

$$\psi_L = \begin{pmatrix} u^c \\ u^c \\ u^c \\ \nu_e \\ e^- \\ E^- \end{pmatrix}_L, \quad \chi_L = \begin{pmatrix} U^c \\ U^c \\ N_E \\ E_1^- \\ E_2^- \end{pmatrix}_L,$$

$$\Psi_L = \begin{pmatrix} 0 & d^c & -d^c & d & u & U \\ -d^c & 0 & d^c & d & u & U \\ d^c & -d^c & 0 & d & u & U \\ -d & -d & -d & 0 & \nu_{e1}^c & -N_{E1}^c \\ -u & -u & -u & -\nu_e^c & 0 & E_1^+ \\ -U & -U & -U & N_E^c & -E_1^+ & 0 \end{pmatrix}_L, \tag{5}$$

$$\mathbf{1}: \quad e_L^+, \quad E_L^+, \quad E_{2L}^+, \quad \nu_{SL} \tag{6}$$

where U is a new up-like quark, E^- , E_1^- and E_2^- are new exotic charged leptons and ν_{e1R} , N_{EL} and N_{ER1} are new neutrinos. In order to obtain fermion mass hierarchies among families, discrete symmetries can be introduced to obtain suitable mass matrix ansatz. The additional sterile neutrino ν_S with $X_S = 0$ is necessary to produce see-saw mechanisms between neutrinos [26–28].

- The covariant derivatives for each type of multiplets are defined as follows:

$$D_\mu \psi_a = \partial_\mu \psi_a + i \left(g_6 A_\mu^\alpha (T_\alpha)^b_a \right) \psi_b + i g_X (X_{\bar{\mathbf{6}}})^b_a X'^\mu \psi_b, \tag{7}$$

$$D_\mu \Psi^{ab} = \partial_\mu \Psi^{ab} - i \left(g_6 A_\mu^\alpha (T_\alpha)^{ab}_{cd} \right) \Psi^{cd} - i g_X (X_{\mathbf{15}})^{ab}_{cd} X'^\mu \Psi^{cd}, \tag{8}$$

where Latin indices run from 1 to 6, while Greek indices run from 1 to 35. The $\mathbf{15}$ generators are given by $(T_\alpha)^{ab}_{cd} = (T_\alpha)^a_c \delta^b_d + \delta^a_c (T_\alpha)^b_d$.

- Gauge bosons are described by the $\mathbf{35} = \mathbf{35}$ adjoint representation which obeys the branching rule

$$\mathbf{35} = (\mathbf{8} \otimes \mathbf{1})_0 \oplus (\mathbf{1} \otimes \mathbf{8})_0 \oplus (\mathbf{3} \otimes \bar{\mathbf{3}})_{2/3} \oplus (\bar{\mathbf{3}} \otimes \mathbf{3})_{-2/3} \oplus (\mathbf{1} \otimes \mathbf{1})_0, \tag{9}$$

where $(\mathbf{8} \otimes \mathbf{1})_0$ are identified as QCD gluons; $(\mathbf{1} \otimes \mathbf{8})_0$ are electro-weak gauge bosons which contain W_μ^\pm , $W_{3\mu}^\pm$, $W_{3\mu}^0$, $\bar{W}_{3\mu}^0$, A_μ^3 and A_μ^8 bosons; $(\mathbf{1} \otimes \mathbf{1})_0$ is a neutral boson $B_{Y'\mu}$ from the $U(1)_{Y'}$ symmetry, and $(\mathbf{3} \otimes \bar{\mathbf{3}})_{2/3}$ and $(\bar{\mathbf{3}} \otimes \mathbf{3})_{-2/3}$ are new leptoquark bosons: X_μ with electric charge $2/3$, and $Y_{1\mu}$ and $Y_{2\mu}$ with electric charge $-1/3$, which induces quark–lepton interchange processes. Their corresponding multiplet is:

Table 1
Quantum numbers for the fermionic sector of the model.

Left-handed					Right-handed				
	T_{3L}	X	Y	Q		T_{3L}	X	Y	Q
u	+1/2	+1/3	+1/3	+2/3	u	0	+2/3	+4/3	+2/3
d	-1/2	+1/3	+1/3	-1/3	d	0	+1/3	-2/3	-1/3
U	0	+1/3	+4/3	+2/3	U	0	+2/3	+4/3	+2/3
ν_e	+1/2	-2/3	-1	0	ν_{e1}	0	-1/3	0	0
e^-	-1/2	-2/3	-1	-1	e^-	0	-1	-2	-1
N_E	+1/2	-2/3	-1	0	N_{E1}	+1/2	-1/3	-1	0
E_1^-	-1/2	-2/3	-1	-1	E_1^-	-1/2	-1/3	-1	-1
E^-	0	-2/3	-2	-1	E^-	0	-1	-2	-1
E_2^-	0	-2/3	-2	-1	E_2^-	0	-1	-2	-1

$$\mathbf{A} = \frac{1}{\sqrt{2}} \begin{pmatrix} G^1_1 & G^1_2 & G^1_3 & X^{1c} & Y^{1c} & Y^{1c}_2 \\ G^2_1 & G^2_2 & G^2_3 & X^{2c} & Y^{2c}_1 & Y^{2c}_2 \\ G^3_1 & G^3_2 & G^3_3 & X^{3c} & Y^{3c}_1 & Y^{3c}_2 \\ X^1 & X^2 & X^3 & D_1 & W^+ & W^+_3 \\ Y^1_1 & Y^2_1 & Y^3_1 & W^- & D_2 & W^0_3 \\ Y^1_2 & Y^2_2 & Y^3_2 & W^-_3 & \bar{W}^0_3 & D_3 \end{pmatrix} \tag{10}$$

where $G^1_1 + G^2_2 + G^3_3 = 0$. $D_1 = A^3/\sqrt{2} + A^8/\sqrt{6}$, $D_2 = -A^3/\sqrt{2} + A^8/\sqrt{6}$ and $D_3 = -\sqrt{2}A^8/\sqrt{3}$ are the diagonal $SU(3)_L$ gauge fields. In addition, there is a new electrically neutral vector boson X_μ from $U(1)_X$ symmetry. In total, the $SU(6) \otimes U(1)_X$ group has 36 gauge bosons: eight gluons, eight electroweak bosons, eighteen leptoquark bosons and two electrically neutral bosons.

- Electric charge are constructed using all diagonal generators of $SU(6) \otimes U(1)_X$:

$$Q = aT_3 + \frac{2b}{\sqrt{3}}T_8 + \frac{2c}{\sqrt{6}}T_{15} + \frac{2d}{\sqrt{10}}T_{24} + \frac{2e}{\sqrt{15}}T_{35} + XI_6, \tag{11}$$

where the a, b, c, d, e and f constants are fixed such that the electric charge matches with each charge from the multiplets. We find

$$Q = T_{3L} - \frac{1}{2\sqrt{6}}T_{15} - \frac{1}{2\sqrt{10}}T_{24} + \frac{2}{\sqrt{15}}T_{35} + XI_6 = T_{3L} + \frac{Y}{2}, \tag{12}$$

where Y is the usual hypercharge operator of the SM.

- The fermions contained in the model have the charges listed in Table 1.
- The scalar sector is introduced to obtain the correct SSB chain. The two last symmetry breakings are fulfilled using two Higgs fields represented by sextets $\mathbf{6}$ with $X_{H_1, H_2} = 1/3$. The directions of their VEV, V_1 and v_2 , are selected to obtain electrically neutral vacua. In addition, V_1 is at the TeV scale while v_2 is at the electroweak scale. Two additional Higgs fields represented by $\mathbf{15}$ multiplets with $X_{H_3} = -2/3$ and $X_{H_S} = 1/3$ are introduced to give masses to down quarks and neutrinos, respectively.

The first SSB needs a Higgs field from $\mathbf{35}$ adjoint representation with the following VEV:

$$\langle \Phi \rangle_0 = \mathcal{V}_{\text{GUT}} \text{diag} (+1 \quad +1 \quad +1 \quad -1 \quad -1 \quad -1), \tag{13}$$

where $\mathcal{V}_{\text{GUT}} \sim 10^{17}$ GeV breaks the gauge symmetry to $SU(3)_C \otimes SU(3)_L \otimes U(1)_Y$, providing masses to the leptoquark bosons. For the second and third SSBs, we define the following Higgs scalar multiplets:

$$H_1 = \begin{pmatrix} \phi_1^{1/3} \\ \phi_1^{1/3} \\ \phi_1^{1/3} \\ \varphi_1^+ \\ \varphi_1^0 \\ \frac{\xi_1 + V_1 + i\zeta_1}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} \phi_2^{1/3} \\ \phi_2^{1/3} \\ \phi_2^{1/3} \\ \varphi_2^+ \\ \frac{h_2 + v_2 + i\eta_2}{\sqrt{2}} \\ \varphi_2^0 \end{pmatrix}, \quad (14)$$

$$H_3 = \begin{pmatrix} 0 & \phi_3^{2/3} & -\phi_3^{2/3} & \phi_3^{4/3} & \phi_{31}^{1/3} & \phi_{32}^{1/3} \\ -\phi_3^{2/3} & 0 & \phi_3^{2/3} & \phi_3^{4/3} & \phi_{31}^{1/3} & \phi_{32}^{1/3} \\ \phi_3^{2/3} & -\phi_3^{2/3} & 0 & \phi_3^{4/3} & \phi_{31}^{1/3} & \phi_{32}^{1/3} \\ -\phi_3^{4/3} & -\phi_3^{4/3} & -\phi_3^{4/3} & 0 & \phi_3^+ & -\varphi_3^+ \\ -\phi_{31}^{1/3} & -\phi_{31}^{1/3} & -\phi_{31}^{1/3} & -\phi_3^+ & 0 & \frac{h_3 + v_3 + i\eta_3}{\sqrt{2}} \\ -\phi_{32}^{1/3} & -\phi_{32}^{1/3} & -\phi_{32}^{1/3} & \varphi_3^+ & -\frac{h_3 + v_3 + i\eta_3}{\sqrt{2}} & 0 \end{pmatrix}, \quad (15)$$

$$H_S = \begin{pmatrix} 0 & \phi_S^{-1/3} & -\phi_S^{-1/3} & \phi_S^{1/3} & \phi_{S1}^{-2/3} & \phi_{S2}^{-2/3} \\ -\phi_S^{-1/3} & 0 & \phi_S^{-1/3} & \phi_S^{1/3} & \phi_{S1}^{-2/3} & \phi_{S2}^{-2/3} \\ \phi_S^{-1/3} & -\phi_S^{-1/3} & 0 & \phi_S^{1/3} & \phi_{S1}^{-2/3} & \phi_{S2}^{-2/3} \\ -\phi_S^{1/3} & -\phi_S^{1/3} & -\phi_S^{1/3} & 0 & \frac{\xi_S + V_S - i\zeta_S}{\sqrt{2}} & -\frac{h_S + v_S - i\eta_S}{\sqrt{2}} \\ -\phi_{S1}^{-2/3} & -\phi_{S1}^{-2/3} & -\phi_{S1}^{-2/3} & -\frac{\xi_S + V_S - i\zeta_S}{\sqrt{2}} & 0 & \varphi_S^+ \\ -\phi_{S2}^{-2/3} & -\phi_{S2}^{-2/3} & -\phi_{S2}^{-2/3} & \frac{h_S + v_S - i\eta_S}{\sqrt{2}} & -\varphi_S^+ & 0 \end{pmatrix}, \quad (16)$$

where $V_1, V_S \gg v_2, v_3, v_S \sim 246$ GeV. In this way, the SSB chain is given by Eq. (1).

- Vector boson masses: there are two electroweak SSBs in the low-energy $SU(3)_L \otimes U(1)_X$ model, the first V at TeV and the second v at GeV scale. After the TeV SSB $SU(3)_L \otimes U(1)_X \rightarrow SU(2)_L \otimes U(1)_Y$ the gauge bosons A_μ^8 and X_μ mix them together into the weak hypercharge boson B_μ and a new massive electrically neutral gauge boson $Z_{X\mu}$ through the following mixing matrix with the mixing angle $\tan\theta_X = -\sqrt{3}g/g_X$,

$$\begin{pmatrix} B \\ Z_X \end{pmatrix} = \begin{pmatrix} \cos\theta_X & -\sin\theta_X \\ \sin\theta_X & \cos\theta_X \end{pmatrix} \begin{pmatrix} A^8 \\ -X \end{pmatrix}. \quad (17)$$

The new gauge coupling constant is the electroweak hypercharge $g' = g_X \sin\theta_X = -\sqrt{3}g \cos\theta_X$. The gauge bosons $W_{3\mu}^\pm, W_{3\mu}^0$ and $\bar{W}_{3\mu}^0$ acquire the same mass M_{W_3} which is related to M_{Z_X} by $\sin\theta_W$ in the following way

$$M_{W_3} = \frac{gV}{2}, \quad M_{Z_X} = \frac{gV}{\sqrt{3} \sin\theta_X} = \frac{2}{\sqrt{3}} \frac{M_{W_3}}{\sin\theta_X} \quad (18)$$

where $V^2 = V_1^2 + 2V_2^2$. In addition, the ξ gauge couplings are given by

$$\begin{aligned} \mathcal{L}_{\xi\nu\nu} &= \frac{Vg^2}{3\sin^2\theta_X}\xi Z_{X\mu}Z_X^\mu + \frac{Vg^2}{2}\xi W_{3\mu}^-W_3^{+\mu} + \frac{Vg^2}{2}\xi W_{3\mu}^0\bar{W}_3^{0\mu} \\ &= \frac{M_{Z_1}^2}{V}\xi Z_{X\mu}Z_X^\mu + 2\frac{M_{W_3}^2}{V}\xi W_{3\mu}^-W_3^{+\mu} + 2\frac{M_{W_3}^2}{V}\xi W_{3\mu}^0\bar{W}_3^{0\mu}. \end{aligned} \tag{19}$$

Here ξ does not couple to B_μ because $M_B = 0$. Secondly, for the GeV SSB $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_Q$ will bring the well-known gauge boson mixing through the Weinberg angle $\tan\theta_W = g'/g$

$$\begin{pmatrix} Z_W \\ A \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} A^3 \\ B \end{pmatrix}. \tag{20}$$

The new gauge coupling constant is the electromagnetic charge $e = g_2 \sin\theta_W = g_Y \cos\theta_W$ and the new gauge boson masses are

$$M_{W_3^+} = \frac{g}{2}\sqrt{V^2 + v^2}, \quad M_{W_3^0} = \frac{gV}{2}, \quad M_{W^+} = \frac{gv}{2} \tag{21}$$

where $v^2 = v_2^2 + 2v_3^2 + 2v_5^2 = (246 \text{ GeV})^2$. In addition, $Z_{W\mu}$ and $Z_{X\mu}$ acquire the following masses

$$M_{Z_W} = \frac{gv}{2\cos\theta_W} = \frac{M_W}{\cos\theta_W}, \quad M_{Z_X} = \frac{2}{\sqrt{3}}\frac{M_{W_3}}{\sin\theta_X}. \tag{22}$$

There is an additional gauge boson mixing between the two neutral Z_W and Z_X through the mixing angle $\tan\theta_Z \propto v^2/V^2$,

$$\begin{pmatrix} Z \\ Z' \end{pmatrix} = \begin{pmatrix} \cos\theta_Z & \sin\theta_Z \\ -\sin\theta_Z & \cos\theta_Z \end{pmatrix} \begin{pmatrix} Z_W \\ Z_X \end{pmatrix} \tag{23}$$

obtaining the physical gauge boson masses Z and Z' ,

$$M_Z \approx M_{Z_W}\sqrt{1 + \mathcal{O}\left(\frac{v^2}{V^2}\right)}, \quad M_{Z'} \approx M_{Z_X}\sqrt{1 - \mathcal{O}\left(\frac{v^2}{V^2}\right)}. \tag{24}$$

2.1. Yukawa Lagrangian

The Yukawa Lagrangian that describes interactions between the Higgs and the fermion sector is the following

$$\begin{aligned} -\mathcal{L}_{\text{Yukawa}} &= \sum_{i=1,2} (\psi_{La}^T \hat{C} h_{\psi i} \Psi_L^{ab} H_{ib} + \psi_{La}^T \hat{C} h_{\psi ei} H_i^a e_L^+ + \psi_{La}^T \hat{C} h_{\psi Ei} H_i^a E_L^+ \\ &+ \psi_{La}^T \hat{C} h_{\psi E_{2i}} H_i^a E_{2L}^+ + \chi_{La}^T \hat{C} h_{\chi i} \Psi_L^{ab} H_{ib} + \chi_{La}^T \hat{C} h_{\chi ei} H_i^a e_L^+ \\ &+ \chi_{La}^T \hat{C} h_{\chi Ei} H_i^a E_L^+ + \chi_{La}^T \hat{C} h_{\chi E_{2i}} H_i^a E_{2L}^+) + h_3 \epsilon_{abcdef} \Psi_L^{Tab} \hat{C} \Psi_L^{dc} H_3^{ef} \\ &+ \Psi_L^{Tab} \hat{C} h_S H_{S ab} \nu_{SL} + \nu_{SL}^T \hat{C} M_S \nu_{SL} + h.c., \end{aligned} \tag{25}$$

where $a, \dots, f = 1, \dots, 6$. The terms $\psi_{La}^T \hat{C} h_{\psi i} \Psi_L^{ab} H_{ib}$ and $\chi_{La}^T \hat{C} h_{\chi i} \Psi_L^{ab} H_{ib}$ give masses to up quarks and leptons at the order of $\langle H_i \rangle$ and with Yukawa coupling constants $h_{\psi i}$ and $h_{\chi i}$. Terms

containing couplings with singlet leptons, as for example $\psi_{La}^T \hat{C} h_{\psi ei} H_i^a e_L^+$, give masses to e_L^+ , E_L^+ and E_{2L}^+ with coupling constants $h_{\psi ei}$, $h_{\psi E1}$ and $h_{\psi E2}$, respectively. The term that contains couplings with the scalar fields H_3 , gives masses to down quarks with coupling constant h_3 . The last two terms in Eq. (25) induce see-saw neutrino masses [29–32], where ν_{SL} is a Majorana neutrino of mass M_S which is fixed to give a light neutrino ν_e , with mass at the order of eV.

First, for up quarks, we obtain the following non-diagonal mass matrix,

$$M_{uU}^0 = \begin{pmatrix} h_{\psi 2} v_2 & h_{\psi 1} V_1 \\ h_{\chi 2} v_2 & h_{\chi 1} V_1 \end{pmatrix}. \quad (26)$$

By diagonalizing the symmetric matrix $(M_{uU}^0)^T M_{uU}^0$, we obtain the following masses

$$\begin{aligned} m_U &\approx \sqrt{\frac{h_{\chi 1}^2 + h_{\psi 1}^2}{2}} V_1, \\ m_u &\approx \frac{h_{\chi 1} h_{\psi 2} - h_{\psi 1} h_{\chi 2}}{\sqrt{h_{\chi 1}^2 + h_{\psi 1}^2}} v_2. \end{aligned} \quad (27)$$

Charged leptons acquire masses through the following mass matrix in the (e^-, E^-, E_1^-, E_2^-) basis,

$$M_E = \begin{pmatrix} h_{\psi e 2} v_2 & h_{\psi E 2} v_2 & h_{\psi 1} V_1 & h_{\psi E_{22}} v_2 \\ h_{\psi e 1} V_1 & h_{\psi E 1} V_1 & -h_{\psi 2} v_2 & h_{\psi E_{21}} V_1 \\ h_{\chi e 2} v_2 & h_{\chi E 2} v_2 & h_{\chi 1} V_1 & h_{\chi E_{22}} v_2 \\ h_{\chi e 1} V_1 & h_{\chi E 1} V_1 & -h_{\chi 2} v_2 & h_{\chi E_{21}} V_1 \end{pmatrix}, \quad (28)$$

while neutrinos acquire masses through the following mass matrix in the $(\nu_e, \nu_{e1}^c, N_E, N_{E1}^c, \nu_S)$ basis,

$$M_N = \begin{pmatrix} 0 & h_{\psi 2} v_2 & 0 & -h_{\psi 1} V_1 & 0 \\ h_{\psi 2} v_2 & 0 & h_{\chi 2} v_2 & 0 & h_S V_S \\ 0 & h_{\chi 2} v_2 & 0 & -h_{\chi 1} V_1 & 0 \\ -h_{\psi 1} V_1 & 0 & -h_{\chi 1} V_1 & 0 & h_S v_S \\ 0 & h_S V_S & 0 & h_S v_S & M_S \end{pmatrix}. \quad (29)$$

Finally, the down quark acquire mass proportional to $\langle H_3 \rangle = v_3$,

$$m_d = \sqrt{2} h_3 v_3. \quad (30)$$

2.2. Higgs potential

The interactions between the four Higgs bosons are described by the following scalar potential,

$$\begin{aligned} V(H_1, H_2, H_3, H_S, \Phi) \\ = -\mu_1^2 H_1^\dagger H_1 - \mu_2^2 H_2^\dagger H_2 - \mu_3^2 \text{Tr}(H_3^\dagger H_3) - \mu_S^2 \text{Tr}(H_S^\dagger H_S) - \mu_\Phi^2 \text{Tr}(\Phi)^2 + \\ \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 \text{Tr}(H_3)^4 + \lambda'_3 (\text{Tr}(H_3)^2)^2 + \end{aligned}$$

$$\begin{aligned}
 & \lambda_S \text{Tr}(H_S)^4 + \lambda'_S (\text{Tr}(H_S)^2)^2 + \lambda_\Phi \text{Tr}(\Phi)^4 + \lambda'_\Phi (\text{Tr}(\Phi)^2)^2 + \\
 & \lambda_{12} (H_1^\dagger H_1) (H_2^\dagger H_2) + \lambda_{1S} (H_1^\dagger H_1) \text{Tr}(H_S^\dagger H_S) + \lambda'_{1S} (H_1^\dagger (H_S)^2 H_1) + \\
 & \lambda_{13} (H_1^\dagger H_1) \text{Tr}(H_3)^2 + \lambda'_{13} (H_1^\dagger (H_3)^2 H_1) + \lambda_{2S} (H_2^\dagger H_2) \text{Tr}(H_S^\dagger H_S) + \\
 & \lambda'_{2S} (H_2^\dagger (H_S)^2 H_2) + \lambda_{23} (H_2^\dagger H_2) \text{Tr}(H_3)^2 + \lambda'_{23} (H_2^\dagger (H_3)^2 H_2) + \\
 & \lambda_{3S} (\text{Tr} H_3^2) (\text{Tr} H_S^2) + \lambda'_{3S} \text{Tr}(H_3^\dagger H_3 H_S^\dagger H_S) + \lambda''_{3S} \text{Tr}(H_3^\dagger H_S^\dagger H_S H_3) + \\
 & \lambda_{1\Phi} (H_1^\dagger H_1) \text{Tr}(\Phi)^2 + \lambda'_{1\Phi} (H_1^\dagger (\Phi)^2 H_1) + \lambda_{2\Phi} (H_2^\dagger H_2) \text{Tr}(\Phi)^2 + \\
 & \lambda'_{2\Phi} (H_2^\dagger (\Phi)^2 H_2) + \lambda_{S\Phi} (\text{Tr} H_S^2) (\text{Tr} \Phi^2) + \lambda'_{S\Phi} \text{Tr}(H_S \Phi H_S \Phi) + \\
 & \lambda''_{S\Phi} \text{Tr}(\Phi H_S H_S \Phi) + \lambda_{3\Phi} (\text{Tr} H_3^2) (\text{Tr} \Phi^2) + \lambda'_{3\Phi} \text{Tr}(H_3 \Phi H_3 \Phi) + \\
 & \lambda''_{3\Phi} \text{Tr}(\Phi H_3 H_3 \Phi).
 \end{aligned} \tag{31}$$

From H_2 , H_3 and H_S (equations (14), (15) and (16)) we obtain three electroweak Higgs doublets which break $SU(2)_L \times U(1)_Y$ into $U(1)_Q$. They are expressed as follows,

$$H_{2EW} = \begin{pmatrix} \varphi_2^+ \\ \frac{h_2 + v_2 + i\eta_2}{\sqrt{2}} \end{pmatrix}, \quad H_{3EW} = \begin{pmatrix} \varphi_3^+ \\ \frac{h_3 + v_3 + i\eta_3}{\sqrt{2}} \end{pmatrix}, \quad H_{SEW} = \begin{pmatrix} \varphi_S^+ \\ \frac{h_S + v_S + i\eta_S}{\sqrt{2}} \end{pmatrix}. \tag{32}$$

Thus, the model contains an effective three Higgs doublet model. For the charged sector, φ_2^\pm , φ_3^\pm and φ_S^\pm rotate into the Goldstone bosons G^\pm associated to W^\pm , and the physical charged Higgs bosons H_1^\pm and H_2^\pm .

2.3. Couplings with ξ

As we mentioned before, from the mixing terms between the real fields ξ_1 in H_1 and ξ_S in H_S , we obtain two real scalar fields: our candidate for the 750 GeV signal ξ , and one ξ' at the TeV scale. In particular, we are interested in the following trilinear terms coming from the quartic couplings between the weak multiplets of the Higgs potential Eq. (31),

$$V_{\text{trilinear}} = \lambda_{H_1} V \xi H_1^+ H_1^- + \lambda_{H_2} V \xi H_2^+ H_2^- + \lambda_{13} V \xi \phi_3^+ \phi_3^- \tag{33}$$

where λ_{H_1} and λ_{H_2} are linear combinations of λ_{12} , λ_{13} and λ_{1S} . The field ϕ_3^\pm is a charged singlet Higgs-like boson coming from the 15-dimensional representation H_3 in Eq. (15). For simplicity, we choose $\lambda_H = \lambda_{H_1} \sim \lambda_{H_2} \sim \lambda_{13}$. Thus, the equation (33) becomes

$$V_{\text{trilinear}} = \lambda_H V \xi (H_1^+ H_1^- + H_2^+ H_2^- + \phi_3^+ \phi_3^-). \tag{34}$$

For the vector boson sector, for simplicity and following [33] we consider general interactions of the form

$$g_\gamma W_3 W_3 = \kappa g_{WW}^{\text{SM}}, \quad g_{\gamma H^+ H^-} = \lambda (p_1 - p_2)^\mu, \tag{35}$$

$$g_{Z W_3 W_3} = \kappa' g_{ZW}^{\text{SM}}, \quad g_{Z H^+ H^-} = \lambda' (p_1 - p_2)^\mu, \quad g_{Z H^+ W_3^-} = \eta m W_3 g^{\mu\nu}. \tag{36}$$

In addition, from the fact that the scalar boson ξ has not electroweak isospin and hypercharge, its couplings with the A_μ^3 and B_μ gauge bosons are completely null, hence after the electroweak SSB at the GeV scale the ξ boson remains without interaction with A_μ and $Z_{W\mu}$. Moreover, as the gauge bosons $Z_{W\mu}$ and $Z_{X\mu}$ mix them together into the physical gauge bosons Z_μ and Z'_μ ,

there could be some interaction between ξ and Z_μ . However, it is strongly suppressed by the Z -mixing angle $\tan\theta_Z \propto v^2/V^2$.

Finally, for the fermionic sector, the flavor eigenstates of quarks are related to their mass eigenstates through the following mixing matrix,

$$\begin{pmatrix} u' \\ c' \\ t' \\ U' \\ C' \\ T' \end{pmatrix} = \left(\begin{array}{ccc|ccc} R_{uu} & R_{uc} & R_{ut} & R_{uU} & R_{uC} & R_{uT} \\ R_{cu} & R_{cc} & R_{ct} & R_{cU} & R_{cC} & R_{cT} \\ R_{tu} & R_{tc} & R_{tt} & R_{tU} & R_{tC} & R_{tT} \\ \hline R_{Uu} & R_{Uc} & R_{Ut} & R_{UU} & R_{UC} & R_{UT} \\ R_{Cu} & R_{Cc} & R_{Ct} & R_{CU} & R_{CC} & R_{CT} \\ R_{Tu} & R_{Tc} & R_{Tt} & R_{TU} & R_{TC} & R_{TT} \end{array} \right) \begin{pmatrix} u \\ c \\ t \\ U \\ C \\ T \end{pmatrix}. \quad (37)$$

The off-diagonal blocks mix SM and non-SM quarks. In particular, the t and U quarks are related by

$$\begin{pmatrix} t' \\ U' \end{pmatrix} = \left(\begin{array}{c|c} R_{tt} & R_{tU} \\ \hline R_{Ut} & R_{UU} \end{array} \right) \begin{pmatrix} t \\ U \end{pmatrix} \quad (38)$$

where $R_{tt} = R_{UU} = \cos\theta_{tU}$ and $R_{Ut} = -R_{tU} = \sin\theta_{tU} \propto v_2/V_1$. Since $v_2/V_1 \ll 1$ the mixing between t and U is small resulting in the suppression of the coupling between ξ and t . In the same way the off-diagonal components of the mixing matrix in Eq. (37) are proportional to v_2/V_1 resulting in the suppression of these mixing terms splitting the up-quark sector in SM and non-SM up-quarks.

3. Diphoton decay

For the analysis of the diphoton decay, we take into account all the possible decay modes of the 750 GeV candidate. Firstly, the masses of charged Higgs bosons $H_{1,2}^\pm$ and ϕ_3^\pm are at the TeV scale, so the decay of ξ at tree level into these charged Higgs bosons in the model is kinematically forbidden. Secondly, when the SSB $SU(3)_L \rightarrow SU(2)_L$ takes place, U_L does not acquire a $SU(2)_L$ quantum number resulting in a $SU(2)_L$ singlet. As a consequence of that, the decay $\xi \rightarrow WW$ is forbidden too. Thirdly, the $\xi \rightarrow ZZ$ decay is negligible at tree-level as it is suppressed by the Z -mixing angle $\tan\theta_Z \propto v^2/V^2$. Similarly, the $\xi \rightarrow t\bar{t}$ decay is negligible at tree-level as the $\xi - t$ coupling is proportional to $\sin\theta_{tU} \propto v_2/V_1$. Finally, the decay $\xi \rightarrow hh$ is strongly constrained by ATLAS and CMS at 95% CL [34]. In this way, we obtain the following total decay width for ξ ,

$$\Gamma = \Gamma_{\gamma\gamma} + \Gamma_{gg} + \Gamma_{Z\gamma} + \Gamma_{ZZ}. \quad (39)$$

The experimentally reported width of the resonance ranges between 0 and 100 GeV, and can be larger ('broad') or smaller ('narrow') than the experimental resolution of about 6–10 GeV [35]. The best-fit width reported by the ATLAS Collaboration is $\Gamma \sim 45 \text{ GeV} \sim 0.06 m_\xi$. So, in view of some tension with the CMS data we use three approximations for the decay width:

- A width approximation given by the experimentally reported width from the ATLAS Collaboration $\Gamma = 45 \text{ GeV}$.

- A width approximation for a narrower resonance with $\Gamma = 1 \text{ GeV}$.
- An approximation given only by one loop contributions, $\Gamma = \Gamma_{\gamma\gamma} + \Gamma_{gg} + \Gamma_{Z\gamma} + \Gamma_{ZZ}$.

Following [33,36] the decay rates of ξ are given by

$$\begin{aligned} \Gamma(\xi \rightarrow \gamma\gamma) &= \frac{\alpha^2 h_U^2 m_\xi^3}{512\pi^3 m_U^2} \left| \sum_i N_{ci} Q_i^2 F_i \right|^2, \\ \Gamma(\xi \rightarrow gg) &= \frac{\alpha_s^2 h_U^2 m_\xi^3}{64\pi^3 m_U^2} \left| \sum_i F_i \right|^2, \\ \Gamma(\xi \rightarrow Z\gamma) &= \frac{\alpha^2 h_U^2 m_\xi^3}{64\pi^3 m_U^2} \left(1 - \frac{m_Z^2}{m_\xi^2} \right)^3 \left| \frac{7\kappa^2 c_w}{2s_w} + \frac{2}{3} \sum_i N_{ci} Q_i^2 + \frac{\lambda^2}{24\pi\alpha} \right|^2, \\ \Gamma(\xi \rightarrow ZZ) &= \frac{\alpha^2 h_U^2 m_\xi^3}{128\pi^3 m_U^2} \mathcal{P} \left(\frac{m_Z^2}{m_\xi^2} \right) \left| \frac{7\kappa^2 c_w^2}{2s_w^2} - \frac{2}{3} \sum_i N_{ci} Q_i^2 - \frac{\lambda^2}{24\pi\alpha} - \frac{\eta^2}{96\pi\alpha} \right|^2 \end{aligned} \quad (40)$$

where $\mathcal{P}(x) = \sqrt{1-4x}(1-4x+6x^2)$ is a factor correcting the massive final states in the decay width. Here, $h_U^2 = (h_{\chi 1}^2 + h_{\psi 1}^2)/2$, i.e., we assume the same Yukawa coupling for the three families for simplicity and with the same mass m_U and we have made $\kappa = \kappa'$, $\lambda = \lambda'$. The functions F_i

$$F_i(\tau_i) = \begin{cases} 2 + 3\tau_i + 3\tau_i(2 - \tau_i)f(\tau_i) & i = 1 \\ -2\tau_i [1 + (1 - \tau_i)f(\tau_i)] & i = 1/2 \\ \frac{1}{2}\tau_i [1 - \tau_i f(\tau_i)] & i = 0 \end{cases} \quad (41)$$

are spin dependent functions for the loop factor. For $\tau_i > 1$ the function $f(\tau_i)$ is

$$f(\tau_i) = \left[\arcsin \left(\frac{1}{\sqrt{\tau_i}} \right) \right]^2, \quad (42)$$

with $\tau_i = 4m_i^2/m_\xi^2$, where the masses of the particles into the loop are $m_i > 375 \text{ GeV}$.

3.1. Production cross section

The total cross section $\sigma(pp \rightarrow \xi \rightarrow \gamma\gamma)$ in the narrow width approximation is given by

$$\sigma(pp \rightarrow \xi \rightarrow \gamma\gamma) = \frac{C_{gg}\Gamma(\xi \rightarrow gg)}{s m_\xi \Gamma} \Gamma(\xi \rightarrow \gamma\gamma), \quad (43)$$

where

$$C_{gg} = \frac{\pi^2}{8} \int_{m_\xi/s}^1 \frac{dx}{x} g(x) g(m_\xi^2/sx) \quad (44)$$

is the dimensionless partonic integral computed at the scale $\mu = m_\xi = 750 \text{ GeV}$ and center of mass energy $\sqrt{s} = 13 \text{ TeV}$, obtaining $C_{gg} = 2137$ [37]. For the analysis we have taken the combined-rescaled results for the cross section from CMS and ATLAS, $\sigma(pp \rightarrow \xi \rightarrow \gamma\gamma) = (2-8) \text{ fb}$ equally valid for $\sqrt{s} = 8 \text{ TeV}$ and $C_{gg} = 174$ [34].

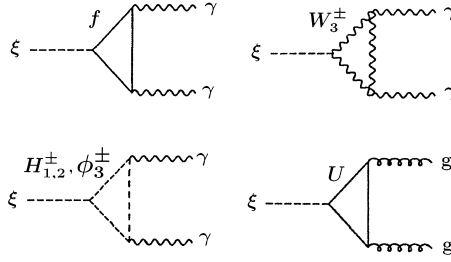


Fig. 1. One loop processes involved in the decay widths Γ_{gg} and $\Gamma_{\gamma\gamma}$. In this figure, $f = \{U, E^-, E_1^-, E_2^-\}$.

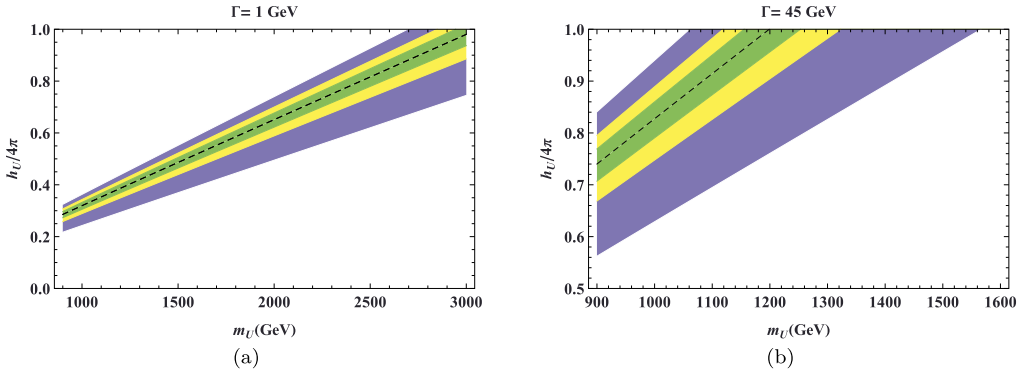


Fig. 2. Contour plots of the production cross-section $\sigma(pp \rightarrow \xi \rightarrow \gamma\gamma)$ in femtobarns. The dashed line corresponds to the central value at 6 fb, and the shaded bands corresponds to regions at 68.3% (green), 95.5% (yellow) and 99.7% (light blue) C.L. exclusion limits from ATLAS and CMS combined data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 1 shows all the possible one loop contributions from exotic charged Higgs bosons, gauge bosons and fermions. In the fermionic loop to $\gamma\gamma$ we take into account the multiplicity coming from the three families, i.e., three exotic quarks and nine exotic charged leptons. For this reason, the contribution coming from the charged Higgs bosons is almost negligible. We also take $m_{W_3^\pm} \sim 3$ TeV according to experimental constraints obtained by ATLAS and CMS Collaboration [38]. However, for $m_{W_3^\pm} \sim 3$ TeV the associated form factor F_1 reaches its asymptotic value so the cross section dependence on $m_{W_3^\pm}$ is suppressed. So, the production cross section will depend only on the Yukawa coupling h_U , on the mass of the quarks m_U and on the exotic charged lepton masses m_E, m_{E_1} and m_{E_2} . From the lower bound reported by the ATLAS Collaboration searches on exotic heavy charged leptons [39] we set $m_E = m_{E_1} = m_{E_2} \sim 600$ GeV.

Taking into account all the above conditions, we display in Fig. 2 contour plots of the production cross-section $\sigma(pp \rightarrow \xi \rightarrow \gamma\gamma)$ as function of the up-type quark mass m_U and the Yukawa coupling normalized as $h_U/4\pi$ for $\Gamma = 1$ GeV and $\Gamma = 45$ GeV. The lower bound of 900 GeV for m_U corresponds to the reported value in recent searches on top- and bottom-like heavy quarks from ATLAS and CMS Collaborations [40] and the upper bound of 3 TeV corresponds to the asymptotic value obtained from the fermionic form factor $F_{1/2}$. We obtain allowed regions for both $\Gamma = 1$ GeV and $\Gamma = 45$ GeV widths for the scalar particle of 750 GeV in agreement with the ATLAS and CMS Collaborations data. In Fig. 2 (a) we obtain values for $h_U/4\pi$ from 0.2 to

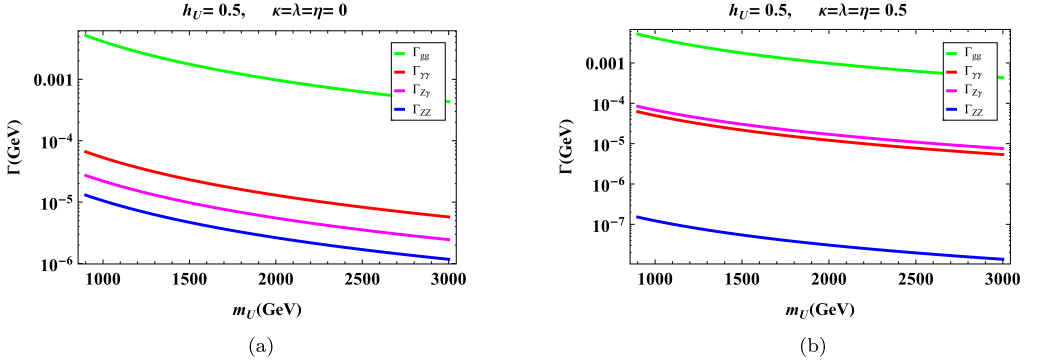


Fig. 3. Different decay channels for the 750 GeV candidate at one loop level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1.0 and an allowed mass region for the up-like quark from 900 GeV to 3.0 TeV at 99.7% CL. In Fig. 2 (b) the model is excluded for $h_U/4\pi < 0.6$ and $m_U > 1.5$ TeV at 99.7% CL.

Finally, for the case $\Gamma = \Gamma_{\gamma\gamma} + \Gamma_{gg} + \Gamma_{Z\gamma} + \Gamma_{ZZ}$, we show in Fig. 3 the different contributions in Eq. (40) for the decay width of ξ . From Fig. 3 (a), the case $\kappa = \lambda = \eta = 0$ and $h_U = 0.5$ corresponds to pure fermionic contributions into the loops. We can see that the contributions (ignoring the dominant Γ_{gg}) $\Gamma_{\gamma\gamma}$, $\Gamma_{Z\gamma}$, Γ_{ZZ} have branching ratios of order 64%, 25%, 11% respectively. On the other hand, the case $\kappa = \lambda = \eta = 0.5$ and $h_U = 0.5$ in Fig. 3 (b) corresponds to both fermionic and bosonic contributions into the loop with $\text{BR}_{\gamma\gamma}$, $\text{BR}_{Z\gamma}$, BR_{ZZ} of order 43%, 56%, 1% respectively.

In this way, and taking into account current bounds on $\Gamma_{Z\gamma}/\Gamma_{\gamma\gamma}$ and $\Gamma_{ZZ}/\Gamma_{\gamma\gamma}$ [41], we display in Fig. 4 contour plots of the production cross-section $\sigma(pp \rightarrow \xi \rightarrow \gamma\gamma)$ in the $\Gamma_{Z\gamma}/\Gamma_{\gamma\gamma} - \Gamma_{ZZ}/\Gamma_{\gamma\gamma}$ plane. For simplicity, we have set $\lambda_{eff} \equiv \kappa = \lambda = \eta = h_U$ in such a way that the contour plots only depend on m_U and λ_{eff} . In general, for low values of m_U the ratio $\Gamma_{Z\gamma}/\Gamma_{\gamma\gamma}$ is of order $\Gamma_{Z\gamma}/\Gamma_{\gamma\gamma} \sim 1$, and for greater values of m_U we have $\Gamma_{Z\gamma}/\Gamma_{\gamma\gamma} < 1$. We also observe that the greater the ratio $\Gamma_{Z\gamma}/\Gamma_{\gamma\gamma}$, the stronger the coupling λ_{eff} . However, if $\lambda_{eff} > 3$ the model is completely excluded by the bound $\Gamma_{Z\gamma} < 20\Gamma_{\gamma\gamma}$ for all m_U .

4. Summary

We have presented an anomaly-free model based on the electroweak-strong unification group $SU(6) \otimes U(1)_X$, containing the $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$ as a subgroup. We break the gauge symmetry down to $SU(3)_C \otimes U(1)_Q$ and at the same time give masses to the fermion fields in the model in a consistent way by five Higgs fields Φ , H_1 , H_2 , H_3 and H_5 . These Higgs fields and their VEVs set two different mass scales: $v = 246$ GeV $\ll V$. From the mixing terms between the real fields ξ_1 in H_1 and ξ_5 in H_5 , we obtain two real scalar fields: our candidate for the 750 GeV signal ξ , and one ξ' at the TeV scale. For the analysis of the diphoton decay, we take into account all the possible decay modes of the 750 GeV candidate considering three approximations for the decay width: $\Gamma = 1$ GeV, $\Gamma = 45$ GeV and $\Gamma = \Gamma_{\gamma\gamma} + \Gamma_{gg} + \Gamma_{Z\gamma} + \Gamma_{ZZ}$. Then, taking various simplified assumptions on the parameter space, we show that the states U , E , E_1 , E_2 , W_3^\pm , $H_{1,2}^\pm$ and ϕ_3^\pm into the loop can explain the diphoton excess for each one of the width approximations according to ATLAS and CMS bounds on all the particle masses involved and on the decay widths $\Gamma_{Z\gamma}$ and Γ_{ZZ} .

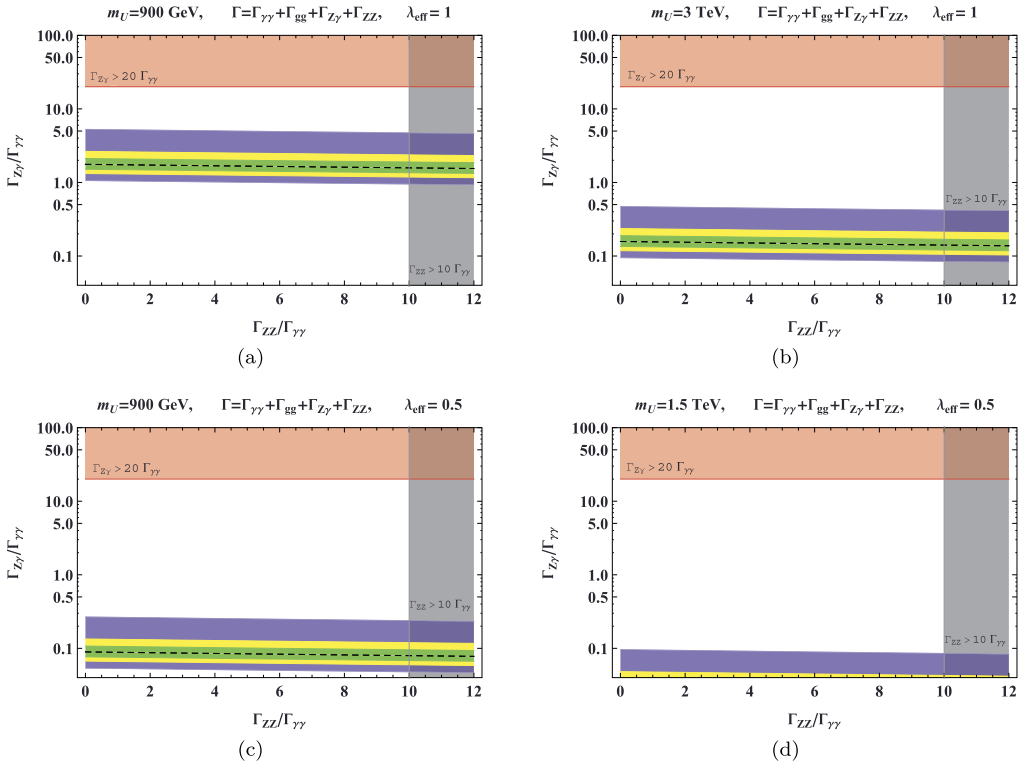


Fig. 4. Contour plots of the production cross-section $\sigma(pp \rightarrow \xi \rightarrow \gamma\gamma)$ in femtobarns. The dashed line corresponds to the central value at 6 fb, and the shaded bands corresponds to regions at 68.3% (green), 95.5% (yellow) and 99.7% (light blue) C.L. exclusion limits from ATLAS and CMS combined data. The shaded red and gray regions are excluded. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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