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LHC diphoton resonance at 750 GeV as an indication of $SU(3)_L \times U(1)_X$ electroweak symmetry

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Abstract The LHC collaborations ATLAS and CMS recently reported on the excess of the events in the diphoton final states at the invariant mass of about 750 GeV. In this article we speculate on the possibility that the excess arises from the neutral CP-even component ϕ of the scalar triplet Φ of the $SU(3)_c \times SU(3)_L \times U(1)_X$ (3−3−1) model that has a $U(1)_X$ charge equal to $X = -1/3$ and acquires a vacuum expectation value larger than the electroweak symmetry breaking scale. The interactions of the scalar field ϕ with the photon and gluon pairs are mediated by the virtual vector-like fermions which appear as components of the anomaly-free chiral fermion representations of the 3−3−1 gauge group.

1 Introduction

The experimental ATLAS and CMS collaborations recently presented the results of the analysis of the early data obtained from the second LHC run of the proton–proton collisions at the center-of-mass energy $\sqrt{s} = 13$ TeV [1,2]. Interestingly, both experiments observed the excess of the events with respect to the background in the diphoton final states at the invariant mass of around 750 GeV. The local statistical significance of the ATLAS (CMS) excess is about 3.9 σ (2.6 σ). The ATLAS found the signal in more than a single bin, preferring the large width of the resonance that corresponds to about 6 % of its mass ($\simeq$45 GeV). This feature has not yet been confirmed by the CMS collaboration. The available data from the second run did not reveal additional excess of the leptons or jets at this invariant mass. While it is possible that the reported excess is a random statistical fluctuation, if confirmed it would provide the first direct evidence for physics beyond the Standard Model (SM).

The results of many theoretical studies of the excess have been presented in the literature in the months following the announcement. General analyses of the excess, including surveys of several different specific model realizations can be found in [3–10]. Variety of possibilities to accommodate the excess within the new physics models was presented in e.g. [11–49].

The authors of several articles [3,4,6,9,11,25,50,51] noted the possibility that the electrically charged and colored vector-like fermions can be invoked for the mediation of the scalar boson interactions to the photon and gluon pairs. In this article we identify the excess with the scalar boson within the extended electroweak gauge group $SU(3)_L \times U(1)_X$, that is, a component of the $SU(3)_L$ triplet with $U(1)_X$ charge $X = -1/3$. The anomaly free assignment of the fermion fields to the representations of the 3-3-1 group[1] leads to the appearance of the non-standard leptons and quarks that are vector-like under the SM gauge group. These fermions mediate the interactions of the scalar boson with the gluon and photon pairs at the loop(s) level.

2 The model

The 3-3-1 extension of the SM was first proposed in the late 70s [52]. Several versions of the model have been subsequently studied; see e.g. [53–57]. Minimal versions do not include additional chiral fermion multiplets under the $SU(3)_L \times U(1)_X$ group, beyond those that contain three generations of the standard leptons and quarks. Many phenomenological aspects of the model have been investigated so far. As an example, the model can include the Peccei–Quinn symmetry, which leads to the possible solution of the

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[1] In the following we refer to the models that are based on this gauge group as 3-3-1 models, as the $SU(3)_c$ group factor of the QCD remains intact.

strong-CP problem [58–61]. The studies of the models that contain sterile neutrinos in connection with weakly interacting massive fermionic dark matter candidates were reported in Refs. [62–65], and the explorations of the fermion mass and mixing patterns in [63,66–85].

We now briefly review the field content of the model and the interactions relevant for the present discussion. The electric charge generator can be expressed as the following linear combination:

$$Q = T_3 + \beta T_8 + XI, \qquad (1)$$

where the T_i are the generators of the $SU(3)_L$ group, which act on the triplet representation via the usual Gell-Mann matrices λ_i, i.e. $T_i = 1/2\lambda_i$. The X is the charge of the given representation under the $U(1)_X$ group factor, the I stands for an identity matrix, while β is an arbitrary real parameter.

Several versions of the 3-3-1 models differ in the choice of the β parameter. The most studied versions correspond to $\beta = \pm 1/\sqrt{3}$ [52] and $\beta = \pm\sqrt{3}$ [54,56]. The standard left (right) handed quarks and leptons are embedded into the chiral representations of the $SU(3)_L \times U(1)_X$, i.e. as triplets (singlets) of the $SU(3)_L$ group with the corresponding non-anomalous assignments of the X charges. These representations contain non-standard fermions, which reside in the vector-like representations of the SM gauge group. We denote the new quarks by the letter J and the new leptons by the symbol $\tilde{e}$. It then follows that the cancellation of the chiral anomalies requires that one of the quark generations resides in different representation of the gauge group than the remaining two. As a consequence, one finds that the number of chiral fermion generations is a positive integer multiple of the number of colors, which provides theoretical support to the observation of the existence of three generations of leptons and quarks. For concreteness, we assign the first two generations of left-handed quarks to the triplets of $SU(3)_L$ and the third generation to the antitriplet representation. The assignments of the X-charges are easily determined using the formula (1) and requirement that the standard leptons and quarks have correct electric charges. It turns out that the X-charge of the first two generations of the left-handed triplets is given by $X_{Q_L^{1,2}} = 1/6 - \beta/(2\sqrt{3})$, while for the third generation antitriplet $X_{Q_L^3} = 1/6 + \beta/(2\sqrt{3})$. The corresponding X-charges of the right-handed quarks are equal to their electric charges, and they are given by $X_{u_R^{1,2}, d_R^{1,2}, J_R^{1,2}} = 2/3, -1/3, 1/6 - \beta\sqrt{3}/2$. The non-standard right-handed quark of the third generation carries $X_{J_R^3} = 1/6 + \beta\sqrt{3}/2$. All three generations of the left-handed leptons are assigned to $SU(3)_L$ antitriplets with $X_{L_L} = -1/2 + \beta/(2\sqrt{3})$, while the right-handed leptons are corresponding $SU(3)_L$ singlets and carry $X_{e_R, \tilde{e}_R} = -1, -1/2 + \beta\sqrt{3}/2$. Note that the exotic fermions reside in vector-like representations of the SM gauge group and are singlets under $SU(2)_L$.

The scenarios with $\beta = \pm 1/\sqrt{3}$ introduce the non-standard fermions with the non-exotic electric charges, i.e., charges equal to the electric charge of some standard model fermion. The options with $\beta = \pm\sqrt{3}$ involve large exotic electric charges of the new fermions, which makes these possibilities suitable for the enhancement of the branching fraction of the scalar resonance to the photon pairs. However, this scenario requires the departure from the perturbative description at the scale of several TeV's in order to remain in agreement with the measured value of the weak mixing angle at low energies; see e.g. [86]. Other possibilities, like $\beta = 0, \pm 2/\sqrt{3}$, involve new particles with the exotic (rational) electric charges. The electric charge conservation forbids the decay of the lightest such particle state. The phenomenological viability of such models would then require the detailed analysis of the abundance of the stable exotic charged particles in the Universe's history.

We choose the value of the parameter $\beta = -1/\sqrt{3}$. The electric charges of the vector-like quarks are $Q(J^{1,2}) = 2/3$ and $Q(J^3) = -1/3$, while the electric charges of the vector-like leptons are $Q(\tilde{e}^i) = -1$.

There are several possible choices of the scalar representations responsible for the spontaneous symmetry breaking of the 3-3-1 group to the unbroken $SU(3)_c \times U(1)_{\mathrm{Q}}$; see e.g. [87] for the detailed review. The spontaneous symmetry breaking (SSB) proceeds in two steps. For the first step of breaking down to the SM gauge group we choose a scalar field, Σ^{ij}, that resides in the symmetric (sextet) representation of the $SU(3)_L$ and carries $X_\Sigma = -1/3$. The sextet develops the non-vanishing vacuum expectation value (VEV) in the direction $\langle \Sigma^{33} \rangle = w$, such that $w \gg v_{\mathrm{ew}}$, where $v_{ew} \simeq 246$ GeV is the VEV of the standard Higgs doublet. It turns out that this sextet does not contribute to the masses of the fermions, since $SU(3)_L$ invariant Yukawa term, $\bar{\psi}_L \psi_L^c \Sigma$, also requires $2X_{\psi_L} = X_\Sigma$, which is not satisfied for any of the quark or lepton representations in the model. The spectrum of the massive gauge bosons can be obtained from the kinetic term $Tr[(D_\mu \Sigma)^\dagger (D^\mu \Sigma)]$ using the expression for the covariant derivative for the sextet representation,

$$D_\mu \Sigma^{ij} = \partial_\mu \Sigma^{ij} - i g_L ((W_\mu)^{ik} \Sigma^{kj} + (W_\mu)^{jl} \Sigma^{li}) \\ - i g_X X_\mu \delta^{im} \Sigma^{mj}, \qquad (2)$$

where $W_\mu = W_\mu^a T^a$ denotes the gauge boson field matrix, while X_μ denotes the X gauge boson field. The $SU(2)_L \times U(1)_Y$ symmetry is further broken to the $U(1)_{\mathrm{Q}}$ by two triplet representations of the scalars, ρ with $X_\rho = 2/3$, and η with $X_\eta = -1/3$. These triplets then generate the masses of the SM fermions and $W^\pm$ and Z gauge bosons.

We introduce the triplet Φ with the $U(1)_X$ charge $X = -1/3$ and the VEV pattern $\langle \Phi \rangle = (0, 0, v_\phi)$ to provide masses for the exotic fermions through the Yukawa interactions,

$$-\mathcal{L}_{\rm Y} \supset \sum_{i=1}^{2} y_Q^{(i)} \overline{Q_L^i} \Phi J_R^i + y_Q^{(3)} \overline{Q_L^3} \Phi^* J_R^3 + \sum_{i=1}^{3} y_L^{(i)} \overline{L_L^i} \Phi^* \tilde{e}_R^i + \text{h.c.} \quad (3)$$

We identify the electrically neutral CP-even scalar component ϕ as a candidate for the resonance at the mass equal to 750 GeV. The coupling of the ϕ component of the triplet Φ to the vector-like fermions is then found from the above Yukawa terms after expanding around the vacuum, $\phi(x) \to \phi(x) + v_\phi$. The scalar potential which includes the interactions between the three $SU(3)_L$ scalar triplets contains a large number of unknown couplings and is given for completeness in Appendix A. After the SSB there remain three physical charged scalar bosons with masses around the TeV scale and a doubly charged scalar boson that arises from the sextet and whose mass is expected to be of the order of the scale w. The contributions to the decay rate $\phi \to \gamma\gamma$ from the loops involving charged scalars stem from the trilinear couplings denoted by $C_{\phi S_i^{+(+)} S_i^{-(-)}}$, where S_i labels the physical charged scalar bosons. For example, the trilinear $C_{\phi\sigma_1^{++}\sigma_1^{--}}$ coupling is given by $C_{\phi\sigma_1^{++}\sigma_1^{--}} = \lambda_{14} v_\phi$.

3 The resonance at 750 GeV

The ϕ boson interacts with the photon and gluon pairs via the loops of vector-like quarks to which it couples through the Yukawa terms in the Lagrangian (3). The resonance is produced via gluon–gluon fusion, so that the cross section for the proton–proton scattering into the two-photon final state via the intermediate scalar boson ϕ is given in the narrow width approximation by the formula

$$\sigma(pp \to \phi \to \gamma\gamma) = \frac{\pi^2}{8} \frac{\Gamma(\phi \to gg) \frac{1}{s} \int_{m_\phi^2/s}^{1} \frac{\mathrm{d}x}{x} f_g(x) f_g(m_\phi^2/(sx)) \Gamma(\phi \to \gamma\gamma)}{m_\phi \Gamma_\phi}, \quad (4)$$

where $m_\phi \simeq 750$ GeV is the mass of the resonance, Γ_ϕ its total decay width and $f_g(x)$ denotes the parton distribution function (pdf) of the gluon inside of the proton. We evaluate the partial decay widths in the above formula at the leading order in QCD and include the higher-order QCD corrections by correcting the formula (4) with the multiplicative factor $K^{gg} \sim 1.5$, as is customary.

The corresponding decay widths of the resonance are given at leading order in QCD by

$$\Gamma(\phi \to \gamma\gamma) = \frac{\alpha_{\rm em}^2 m_\phi^3}{512\pi^3} \left| \sum_{i=1}^{3} \frac{N_c}{m_{J_i}} Q_{J_i}^2 y_Q^{(i)} F(x_{J_i}) + \sum_i \frac{1}{m_{\tilde{e}_i}} Q_{\tilde{e}_i}^2 y_L^{(i)} F(x_{\tilde{e}_i}) + \sum_i \frac{2\sqrt{2} C_{S_i} Q_{S_i}^2}{m_\phi^2} S(x_{S_i}) \right|^2 \quad (5)$$

and

$$\Gamma(\phi \to gg) = \frac{\alpha_s^2 m_\phi^3}{256\pi^3} \left| \sum_{i=1,2} \frac{1}{m_{J_i}} y^{(i)} F(x_i) \right|^2, \quad (6)$$

where $x_i = 4m_i^2/m_\phi^2$. The loop functions for fermion contributions $F(x)$ and the charged scalar contribution $S(x)$ are given by the expressions

$$F(x) = 2x\big(1 + (1-x) f(x)\big), \quad S(x) = (-1 + x f(x)) \quad \text{where} \quad f(x) = \big(\arcsin\sqrt{1/x}\big)^2, \quad (7)$$

valid for $x \geq 1$. We use the value of the strong coupling constant $\alpha_s(m_\phi/2) \simeq 0.1$ and the next-to-leading-order (NLO) set of pdfs from [88] (MSTW2008) at the factorization scale $\mu = m_\phi$.

Given that we have $v_{\rm ew} < v_\phi \ll w$ and since the couplings of the 126 GeV Higgs boson are consistent the SM expectations, we consider a benchmark scenario characterized by the absence of mixings between the ϕ resonance and the remaining neutral physical scalar fields. In addition, we assume that the ϕ is kinematically forbidden to decay into charged scalar bosons. Note also that the ϕ boson does not couple at the tree level to W and Z gauge bosons, which acquire their masses from the η and ρ triplets. We have explicitly checked that the contributions of the charged scalars to the diphoton rate is subleading, so that the only relevant contribution arises from the vector-like fermions. For illustration we assume that these fermions are degenerate and show in Fig. 1 the total cross section for the production of the 750 GeV diphoton resonance at the LHC center-of-mass energy $\sqrt{s} = 13$ TeV, as a function of the charged exotic fermion masses m_F, and for several values of the exotic fermion Yukawa couplings, set to be equal to 2.5, 2, and 1.5. Keeping all the Yukawa couplings equal and fixed to the value 1.5, we note that the charged exotic fermion masses cannot be higher than about 800 GeV, in order to provide large enough signal cross section. For charged exotic Yukawa couplings equal to 1.5 and charged exotic fermion masses of 700 GeV, we find a total cross section of 4.7 fb and total width for the ϕ resonance of 45 MeV. In case that the large width of the resonance is confirmed, the present model would be immediately excluded as the explanation of the observed signal. This is the diffi-

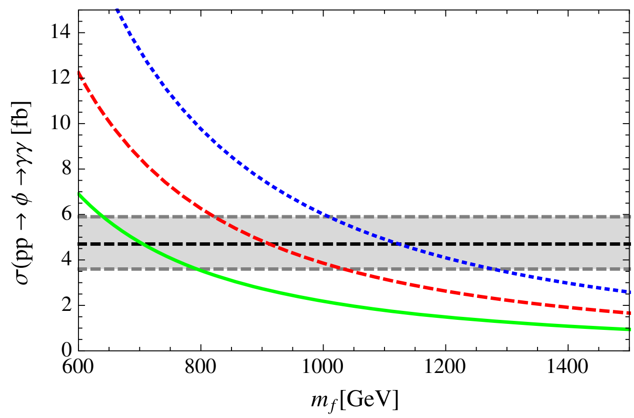

Fig. 1 Total cross section of the production of the resonance ϕ and in its subsequent decay into two photons at the LHC center-of-mass energy 13 TeV as a function of the common mass of the vector-like fermions. The *blue* (*dotted*), *red* (*dashed*), and *green* (*thick*) *lines* correspond to the different values of the common Yukawa couplings equal to 2.5, 2.0, and 1.5, respectively. The *horizontal gray band* corresponds to the recent combination of the ATLAS and CMS measurements, given in Ref. [94]

culty shared by all (the most) weakly coupled models that aim at explaining the excess. Since the vector-like fermions are singlets under the $SU(2)_L$ the decay rate $\Gamma(\phi \to WW)$ is also absent at one loop level. The rate $\Gamma(\phi \to Z\gamma)$ is suppressed with respect to the diphoton rate by the factor $2\tan\theta_W = 0.60$. This factor is easily found by noticing that only the vector couplings of the Z to the fermions contributes to the corresponding amplitude, and in the limit of the heavy scalar boson the amplitude is to a good approximation given by the amplitude of the decay to two photons, albeit with different couplings that involve the weak mixing angle. Furthermore, the rate $\Gamma(\phi \to ZZ)$ is even more suppressed than the rate $\Gamma(\phi \to Z\gamma)$, since it is suppressed with respect to the diphoton rate by the factor $\tan^4\theta_W = 0.08$.

Note that the vector-like fermions may have the couplings to the standard fermions, i.e. terms of the type $\tilde{y}_Q^{ij}\bar{Q}_L^i\Phi u_R^j$. This applies also to the standard down-type quarks and charged leptons. After the Φ develops the VEV, these terms contribute to the quark (charged lepton) mass matrices. The mixing then causes the deviations from the unitarity of the standard Cabibbo–Kobayashi–Maskawa (CKM) matrix, and the observable effects in the Z-pole and electroweak precision observables. These effects are very tightly constrained from the available measurements [89–91]. In order to avoid these constraints we need to set the Yukawa couplings in the corresponding mixing terms to some small values. This can be achieved, at the formal level, by imposing discrete symmetry as shown in Refs. [73,81,82,84,85]. Although technically natural, setting these couplings to small values would constitute the new flavor hierarchy problem, especially if we keep in mind that the couplings that induce the $\phi \to \gamma\gamma$ need to be rather large. The absence of mixings between the SM and exotic quarks will imply that the exotic fermions will not exhibit flavor changing decays into SM quarks and gauge (or Higgs) bosons. After being pair produced they will decay into the standard fermions and the intermediate states of heavy gauge bosons, which in turn decay into the pairs of the standard fermions; see e.g. [92]. The precise signature of the decays of the vector-like fermions depends on details of the spectrum and other parameters of the model. The present lower bounds from the LHC on the masses of the Z' gauge bosons in the 3-3-1 models reach around 2.5 TeV [93]. One can translate these bounds on the order of magnitude of the scale w. The suppression of the decay rates involving SM gauge bosons and the large masses of the nonstandard gauge bosons then imply long-lived vector-like fermions, whose masses are constrained at the LHC via Drell–Yan processes in proton–proton collisions. The current lower bounds on such particles are all below 600 GeV for the electric charges considered in our present paper [95,96]. We plan to study the details of the corresponding collider signatures in the future.

4 Summary

To summarize, we point out that the diphoton signal recently observed by the ATLAS and CMS collaborations at the invariant mass ∼750 GeV could arise from the ϕ, electrically neutral CP-even component of one of the scalar triplets representation of the 3-3-1 model. Its couplings to photons and gluons are mediated by the loops that involve exotic vector-like fermions. Such fermions appear as components of the anomaly-free fermion representations. In order to reproduce the observed signal, the vector-like fermions need to be light (around 1 TeV) and couple to the ϕ boson rather strongly. On the other hand the mixings of the vector-like fermions to the standard chiral fermions needs to be highly suppressed in order to remain in accordance with the precision experiments.

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Appendix A: Scalar potential

The scalar potential which includes the interactions between the three $SU(3)_L$ scalar triplets and with the scalar sextet is given by

$$
\begin{aligned}
V_H =\ & \mu_\chi^2(\Phi^\dagger\Phi) + \mu_\eta^2(\eta^\dagger\eta) + \mu_\rho^2(\rho^\dagger\rho) \\
& + f_1(\eta_i\Phi_j\rho_k\varepsilon^{ijk} + \mathrm{H.c}) + \lambda_1(\Phi^\dagger\Phi)(\Phi^\dagger\Phi) \\
& + \lambda_2(\rho^\dagger\rho)(\rho^\dagger\rho) + \lambda_3(\eta^\dagger\eta)(\eta^\dagger\eta) \\
& + \lambda_4(\Phi^\dagger\Phi)(\rho^\dagger\rho) + \lambda_5(\Phi^\dagger\Phi)(\eta^\dagger\eta) \\
& + \lambda_6(\rho^\dagger\rho)(\eta^\dagger\eta) + \lambda_7(\Phi^\dagger\eta)(\eta^\dagger\Phi) + \lambda_8(\Phi^\dagger\rho)(\rho^\dagger\Phi) \\
& + \lambda_9(\rho^\dagger\eta)(\eta^\dagger\rho) + \mu_\Sigma^2(\Sigma_{ij}\Sigma^{ij}) + f_2(\eta_i\rho_j\Sigma^{ij} + \mathrm{H.c}) \\
& + f_3(\Phi_i\rho_j\Sigma^{ij} + \mathrm{H.c}) \\
& + \lambda_{10}(\Sigma_{ij}\Sigma^{ij})(\Sigma_{kl}\Sigma^{kl}) + \lambda_{11}(\Sigma_{ij}\Sigma^{il})(\Sigma_{kl}\Sigma^{jk}) \\
& + \lambda_{12}(\eta^\dagger\eta)(\Sigma_{kl}\Sigma^{kl}) \\
& + \lambda_{13}(\rho^\dagger\rho)(\Sigma_{kl}\Sigma^{kl}) + \lambda_{14}(\Phi^\dagger\Phi) \\
& \times(\Sigma_{kl}\Sigma^{kl}) + \lambda_{15}[(\Phi^\dagger\eta)(\Sigma_{kl}\Sigma^{kl}) + \mathrm{H.c}] \\
& + \lambda_{16}\eta^i\Sigma_{ij}\Sigma^{jk}\eta_k + \lambda_{17}\rho^i\Sigma_{ij}\Sigma^{jk}\rho_k \\
& + \lambda_{18}\Phi^i\Sigma_{ij}\Sigma^{jk}\Phi_k + \lambda_{19}\eta^i\Sigma_{ij}\Sigma^{jk}\Phi_k
\end{aligned}
\tag{A.1}
$$

where the three scalar triplets and the sextet are given in terms of the components:

$$
\Phi = \begin{pmatrix} \phi_1^0 \\ \phi_2^- \\ \frac{1}{\sqrt{2}}(\upsilon_\phi + \phi \pm i\zeta_\phi) \end{pmatrix}, \quad \rho = \begin{pmatrix} \rho_1^+ \\ \frac{1}{\sqrt{2}}(\upsilon_\rho + \xi_\rho \pm i\zeta_\rho) \\ \rho_3^+ \end{pmatrix},
$$

$$
\eta = \begin{pmatrix} \frac{1}{\sqrt{2}}(\upsilon_\eta + \xi_\eta \pm i\zeta_\eta) \\ \eta_2^- \\ \eta_3^0 \end{pmatrix}, \quad \Sigma = \begin{pmatrix} \sigma_1^0 & \sigma_1^- & \sigma_2^0 \\ \sigma_1^- & \sigma_1^{--} & \sigma_2^- \\ \sigma_2^0 & \sigma_2^- & w + \sigma_3^0 \end{pmatrix}. \tag{A.2}
$$

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