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On the TeV Origin of New Heavy Scalars

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Abstract. Given the Run2 Large Hadron Collider at $\sqrt{s} = 13$ TeV and the diphoton anomaly observed by ATLAS and CMS, a TeV scale origin Λ_{TeV} of a new resonance trough a diphoton excess is proposed. For that, a singlet scalar S is considered and its relevant couplings to the Standard Model as well as to the new fermions, i.e., quarks, are discussed. The key feature is the extraction of reliable information on the portal structure of the combined scalar potential, the associated new symmetry breaking, and the mass of the possible scalar.

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A new discovery window for physics beyond the Standard Model (SM) has been opened by the Run2 Large Hadron Collider (LHC) through the provided possibility to study $p-p$ collisions at $\sqrt{s} = 13$ TeV for the first time. In particular, the appearance of new resonances becomes well motivated [1, 2]. Although sometimes it may be just a statistical fluctuation, it really deserves a systematic study of possible new physics explanations. If it is a new heavy particle, it can only be specified by its quantum numbers[1] [3, 4]; and further data will determine whether this resonance is real or no. Though the importance of this excess, it is interesting to ask whether there are simple models where possible new excesses could be explained.

In spite of all these considerations, many models that can account for the excess have been proposed [5–7]. Investigating, whether some of the models may be natural remnants of a high scale physics effect, is also interesting. Most such works are considered to explain the excess without asking about their high scale origin, and interpretation within the SM extensions is dominant [8–12]. In particular, the most obvious question is whether such an additional likely scalar resonance can be part of an extended Higgs sector; in other words, if the new scalar can form a Higgs portal, possibly to a new sector.

In this letter, to answer this question we will remain agnostic about the underlying physics, but assume that a resonantly produced narrow scalar is responsible for the reported signal. We consider in particular the case of a new singlet scalar

[1] In the most likely case, it can be colorless spin-0 or spin-2 states.

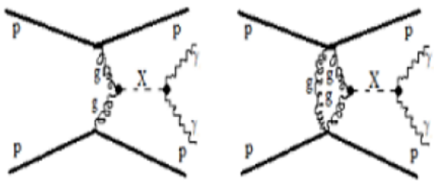

Figure 1. Elastic production of X from $p-p$ collision.

field S, with an effective couplings to the SM sector. This assumption exactly corresponds to recent developments on how to describe deviations from the SM Higgs sector. We investigate the extended scalar potential to discuss the scalar excess S and the related scales and according to the known data.

From a theoretical view, to help in understanding such new scalar possibility, I am going to consider this excess in a wider perspective, and give some guidance on other phenomena we would expect to observe. Let us then suppose that the diphoton decay of a new bosonic particle X,

$$pp \to X \to 2\gamma\,, \tag{1}$$

is behind the possible enhancement; and in the LHC proton–proton collisions $p-p$ it can be produced in quark-quark or gluon-gluon fusions,

$$q\overline{q} \to X \to 2\gamma\,, \tag{2}$$

$$gg \to X \to 2\gamma\,. \tag{3}$$

These productions can be elastic where the intial protons remain intact after the collision as shown in Figure 1, or inelatsic where the initial protons get destroyed after the collision. This is shown in Figure 2.

In the elastic processes (Figure 1), the one with extra-gluons exchange is suppressed with comparison to thoses with simple exchanges. Moreover, these elastic processes are subdominant. And so, thoses where the protons structure is destroyed (inelastic processes) (Figure 2), are dominant. In particular, the gluon

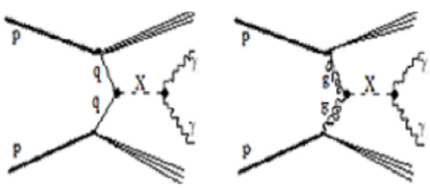

Figure 2. Inelastic production of X from $p-p$ collision.

fusion (3) through heavy $\sim$ TeV colored mediators f^2, which can be the leading production channels in the QCD [13, 14].

$$gg \dashrightarrow \bar{\mathbf{f}}\mathbf{f} \dashrightarrow X \rightarrow 2\gamma\,. \tag{4}$$

Now, let us suppose that the new resonance is a new particle, and because it decays to two photons, it should be non colored and neutral. The simplest one is a singlet scalar $X \equiv S$ such as,

$$C(S) = I(S) = Y(S) = 0\,, \tag{5}$$

where the quantum numbers C, I and Y are the SM charges: color, isospin and hypercharge respectively. This is shown in Figure 3.

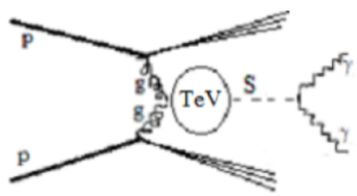

Figure 3. Inelastic production of S from the dominant channel (3) via TeV-fermions.

In this picture, these TeV-fermions, to be colored, are nothing but new quarks $f \equiv \mathbf{q}$, more heavier that ordinary quarks; and thus the dominant channel (5) reads now as,

$$gg \dashrightarrow \mathbf{q}\overline{\mathbf{q}} \dashrightarrow S \rightarrow 2\gamma\,. \tag{6}$$

With this fields and charges content, the corresponding relevant effective Lagrangian involving the new scalar S is,

$$\begin{aligned} \zeta^{\text{eff}}_{S-SM} &= y_{S\mathbf{q}} S\mathbf{q}\overline{\mathbf{q}} \\ &+ \mu_S^2 \left|S\right|^2 + \lambda_S \left|S\right|^4 + \lambda_{SH} \left|S\right|^2 \left|H\right|^2 \\ &+ \Lambda^{-1}_{TeV} \left(C_{gg} S G^{a\mu\nu} G_{a\mu\nu} + C_{\gamma\gamma} S F^{\mu\nu} F_{\mu\nu}\right), \end{aligned} \tag{7}$$

where the first part is the Yukawa-like coupling of the scalar field to the new quarks with the strenght $y_{S\mathbf{q}}$, the second part is the scalar potential, where H refers to the SM Higgs field and μ_S, λ_S and λ_{SH} are coupling constants and the last part is the effective coupling of the scalar S to the $SU(3)_C$ and $U(1)_{EM}$ gauge fields $G^{a\mu\nu}(a = 1, \ldots, 8)$ and $F^{\mu\nu}$ with the strenghts C_{gg} and $C_{\gamma\gamma}$, respectively. Here, instead of focusing on the couplings of the new scalar to the gluons and photons, the attention will be given to its couplings to the Higgs sector as well as to the new quarks $\overline{\mathbf{q}}$. This is pictured in Figure 4.

[2] Such colored mediators are likely new quarks, i.e., four generation quarks, and they are relevant for the mass of the new scalar S.

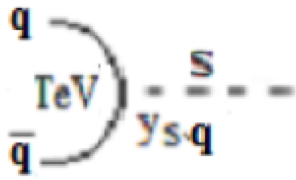

Figure 4. Production of the scalar S through new quarks.

The scalar potential of the model is,

$$V(H,S)=\mu_H^2\left|H\right|^2+\lambda_H\left|H\right|^4+\mu_S^2|S|^2+\lambda_S|S|^4+\lambda_{SH}\left|H\right|^2\left|S\right|^2 \quad (8)$$

with the mixing term $\lambda_{SH}\left|H\right|^2|S|^2$. The v.e.v. $\langle H\rangle\sim 10^2$ GeV and $\langle S\rangle$ of the Higgs field H and the suggested new scalar singlet S are determined by the minimum of this scalar potential (8), obtained by solving the set of the two equations,

$$\frac{\partial V(H,S)}{\partial H}=0; \qquad \frac{\partial V(H,S)}{\partial S}=0\,. \quad (9)$$

Correspondingly, the possible new symmetry associated with the new physics Λ_{TeV} is broken if $-\left[\left(\mu_H^2+\mu_S^2\right)+\left(2\lambda_H+\lambda_{SH}\right)\langle H\rangle^2\right]/2\lambda_S+\lambda_{SH}>0$, in which case S gets a real v.e.v. given by,

$$\langle S\rangle=\sqrt{\frac{-\left[\left(\mu_H^2+\mu_S^2\right)+\left(2\lambda_H+\lambda_{SH}\right)\langle H\rangle^2\right]}{2\lambda_S+\lambda_{SH}}}\,, \quad (10)$$

and the mass of the new scalar as,

$$m_S=\sqrt{-\left(\mu_S^2+\lambda_{SH}\langle H\rangle^2\right)}\,. \quad (11)$$

In this view, the interaction of the new scalar S with the SM arises indirectly through its interaction with the Higgs boson as $\lambda_{SH}\left|S\right|^2\left|H\right|^2$; and because this would influence the decay properties of the discovered Higgs boson with the rate expected in the SM [15, 16], such interaction must be very weak $\lambda_{SH}\ll 1$. This corresponds to a so small mixing between the scalar S and the Higgs H. The mass of the new scalar (11) could then be written as,

$$m_S\simeq\left(1+\frac{\lambda_{SH}\langle H\rangle^2}{2\mu_S^2}\right)\sqrt{-\mu_S^2}\,. \quad (12)$$

Given (7), (10) and (12), we read the mass of the new quarks,

$$m_{\mathbf{q}}\simeq\frac{y_{S\mathbf{q}}\left(1+\lambda_{SH}\langle H\rangle^2/2\mu_S^2\right)}{\sqrt{2\lambda_S}}\sqrt{-\mu_S^2}\sim\Lambda_{\text{TeV}}\,, \quad (13)$$

from which we express the mass of the new scalar in the form,

$$m_S \simeq \frac{\sqrt{2\lambda_S}}{y_{S\mathbf{q}}} \Lambda_{\text{TeV}} \,. \tag{14}$$

At this stage, to continue with this likely higher mass, we have to investigate the relevant scalar couplings; in particular, the self-couplings λ_S and the couplings to the new quarks $y_{S\mathbf{q}}$. For that, we refer to the assumption that the latters are so heavy $m_{\mathbf{q}} \geqslant m_S$ and thus S decays to them is kinematically forbidden. In terms of these couplings constants this could expressed as $\lambda_S < y_{S\mathbf{q}}$. In this approach, for the most likely new scale, i.e., the supersymmetry scale $\Lambda_{\text{TeV}} \sim 10^3$ GeV, a suitable value of the coupling constants report in (14) can gives a mass of the new scalar of $\geqslant 100$ GeV, above the well probed electroweak physics.

In this work, we have considered the possibility that the diphoton anomaly recently observed at the LHC could be part of an extended Higgs sector. Precisely, we have proposed that a new heavy singlet scalar is a very interesting candidate for a possible new resonance during the Run2 LHC, and its existence is well motivated as a test of a Higgs portal scenario in many other models. For that we have discussed the relevant production decay channels for such scalar resonances and studied the corresponding effective lagrangian and thus derived the constraints on the Higgs portal coupling and the associated new symmetry breaking, and approached the mass of the new scalar. Unfortunately, precise results and profound predictions are not allowed because of the approximations of some parameters.

Although many scenarios and production mechanisms have been discussed in the literature, there is a lack of models that give attention to high scale origins in the first place. One such scenario has been presented here where mainly two new parameters, i.e., the mass of the scalar m_S and the energy scale Λ_{TeV} are involved. Both are related and approached according to the known data, with $\Lambda_{\text{TeV}} \sim 10^3$ GeV.

Our proposal predicts that the scalar decaying to a photon pair, is dominantly produced by the strong sector. This gives the additional prediction of this work that the possible excess could be originated from the gluon fusion through new quarks $\sim \Lambda_{\text{TeV}}$ whose mass and coupling $y_{S\mathbf{q}}$ are relevant for the mass of the scalar S. Indeed, we have shown that for the likely supersymmetry scale $\Lambda_{\text{TeV}} \sim 10^3$ GeV particular values of the scalar-new quark coupling $y_{S\mathbf{q}}$ and scalar self-couplings λ_S constants allow for an excess of $\geqslant 100$ GeV. Waitting for more new data, new features will emerge, eliminating the wrong ideas and bringing us closer to the right picture.

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References

[1] [ATLAS Collaboration] (2015) Tech. Rep. ATLAS-CONF-2015-081, CERN, Geneva, Dec.

[2] [CMS Collaboration] (2015) Tech. Rep. CMS-PAS-EXO-15-004, CERN, Geneva.

[3] L.D. Landau (1948) *Dokl. Akad. Nauk Ser. Fiz.* **60** 207; doi:10.1016/B978-0-08010586-4.50070-5.

[4] C.N. Yang (1950) *Phys. Rev.* **77** 242.

[5] L.J. Hall, K. Harigaya and Y. Nomura (2016) arXiv:1512.07904.

[6] P. Ko, T. Nomura, H. Okada and Y. Orikasa (2016) arXiv:1602.07214.

[7] G. Lazarides and Q. Shafi (2016) arXiv:1602.07866.

[8] K. Harigaya and Y. Nomura (2015) arXiv:1512.04850.

[9] Y. Mambrini, G. Arcadi, and A. Djouadi (2015) arXiv:1512.04913.

[10] S.D. McDermott, P. Meade, and H. Ramani (2015) arXiv:1512.05326.

[11] C. Petersson and R. Torre (2016) arXiv:1512.05333.

[12] M.T. Arun and P. Saha (2016) arXiv:1512.06335.

[13] Y. Nakai, R. Sato and K. Tobioka (2016) *Phys. Rev. Lett.* **116** 151802.

[14] Y. Bai, J. Berger and R. Lu (2016) *Phys. Rev. D* **93** 076009.

[15] A. Aad, et al. [ATLAS Collaboration] (2012) *Phys. Lett. B* **716** 1.

[16] S. Chatrchyan, et al. [CMS Collaboration] (2012) *Phys. Lett. B* **716** 30.