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New Physics at 1TeV?

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Abstract. We consider the extension of the Standard Model with an extra scalar S which decays can be responsible for the diphoton excess with invariant mass $\sim$ 750 GeV observed at the 13 TeV LHC run. Two scenarios of S production are considered: gluon fusion through a loop of heavy isosinglet quark(s) and photon fusion through a loop of heavy isosinglet leptons. In the second case many heavy leptons are needed or/ and they should have large electric charges in order to reproduce experimental data on $\sigma_{pp\to SX} \cdot \mathrm{Br}(S \to \gamma\gamma)$.

1 Introduction

ATLAS and CMS collaborations recently announced a small enhancement over smooth background of two photon events with invariant mass 750 GeV [1, 2]. Though statistical significance of this enhancement is not large (within 3 standard deviations), it induced a whole bunch of theoretical papers devoted to its interpretation. The reason for this explosive activity is clear: maybe the Standard Model is changed at one TeV scale, and we are witnessing the first sign of New Physics.

Let us suppose that the observed enhancement is due to the $\gamma\gamma$ decay of a new particle. Then it should be a boson with spin different from one: the simplest possibility is a scalar particle S with $m_S = 750$ GeV. Since it decays to photons, it should be neutral and colorless, therefore in pp-collisions it can be produced in gluon-gluon fusion through the loop of colored particles and in photon-photon fusion through the loop of charged particles. Let us suppose that S decays to these particles are kinematically forbidden, otherwise $\mathrm{Br}(S \to \gamma\gamma)$ reduces significantly which makes $S \to \gamma\gamma$ decays unobservable at the LHC.

We suppose that the particles propagating in the loop are Dirac fermions, so they have tree level masses, and that they are $SU(2)_\mathrm{L}$ singlets. Nonzero hypercharges provide couplings of these particles with photon and Z-boson. These particles can be quark(s) (color triplets) T_i or lepton(s) (color singlets) L_i. They couple with S by Yukawa interactions with coupling constants λ^i_T and λ^i_L correspondingly.

This talk is based on the paper [3] written in collaboration with A.N. Rozanov, M.I. Vysotsky, and E.V. Zhemchugov.

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2 Quarkophilic S

In the case of one heavy quark T the following terms should be added to the Standard Model lagrangian:

$$\Delta\mathcal{L} = \tfrac{1}{2}(\partial_\mu S)^2 - \tfrac{1}{2}m_S^2 S^2 + \bar{T}\gamma_\mu(\partial_\mu - \tfrac{i}{2}g_s A_\mu^i \lambda_i - ig'\tfrac{Y_T}{2}B_\mu)T + m_T\bar{T}T + \lambda_T \bar{T}TS, \tag{1}$$

where A_μ^i and B_μ are gluon and $U(1)$ gauge fields respectively, and λ_i are Gell-Mann matrices. S coupling with gluons is generated by the T-quark loop:

$$M_{gg} = \frac{\alpha_s}{6\pi}\frac{\lambda_T}{m_T}F(\beta)G_{\mu\nu}^{(1)}G_{\mu\nu}^{(2)}S, \tag{2}$$

$$\beta = \left(\frac{2m_T}{m_S}\right)^2, \; F(\beta) = \frac{3}{2}\beta\left[1 - (\beta-1)\arctan^2\frac{1}{\sqrt{\beta-1}}\right]. \tag{3}$$

Inclusive cross section of S production in pp collision at the LHC through gluon fusion is given by:

$$\sigma_{pp\to SX} = \frac{\alpha_s^2}{576\pi}\left(\frac{\lambda_T}{m_T}\right)^2 |F(\beta)|^2 m_S^2 \left.\frac{dL_{gg}}{d\hat{s}}\right|_{\hat{s}=m_S^2}, \tag{4}$$

where the so-called gluon-gluon luminosity is given by the integral over gluon distributions:

$$\frac{dL_{gg}}{d\hat{s}} = \frac{1}{s}\int\limits_{\ln\sqrt{\tau_0}}^{-\ln\sqrt{\tau_0}} g(\sqrt{\tau_0}\mathrm{e}^y, Q^2)g(\sqrt{\tau_0}\mathrm{e}^{-y}, Q^2)dy, \tag{5}$$

$\tau_0 = \hat{s}/s$, $s = (13\text{ TeV})^2$, and we use $Q^2 = m_S^2$. Integrating gluon distributions from [4] for $\sqrt{\hat{s}} = 750$ GeV, $\sqrt{s} = 13$ TeV, we get $dL_{gg}/d\hat{s} \approx 4.0$ nb, $m_S^2\, dL_{gg}/d\hat{s} \approx (1/0.69\text{ nb}) \cdot 4.0\text{ nb} \approx 5.8$. In order to take into account gluon loop corrections, (4) should be multiplied by the so-called K-factor which is close to 2 for $\sqrt{s} = 13$ TeV, according to [5] (see also Fig. 2 in [6]).

In this way for $m_T = m_S$ and $\lambda_T = 1$, substituting $\alpha_s(m_S) = 0.090$, we obtain $\sigma_{pp\to SX} \approx 41$ fb, which should be multiplied by $\mathrm{Br}(S \to \gamma\gamma)$ in order to be compared with experimental observations [1, 2]. Total width of S is dominated by the $S \to gg$ decay, and from (2) we get:

$$\Gamma_{S\to gg} = \left(\frac{\alpha_s}{6\pi}\right)^2 \cdot 8\frac{m_S^3\lambda_T^2}{16\pi m_T^2}|F(\beta)|^2 \approx 3.1\text{ MeV}. \tag{6}$$

Thus for the models we consider, the width of S should be much smaller than 45 GeV which is preferred by the ATLAS data. Let us note that CMS data prefer narrow S; see also [7].

T-quark loop contributes to $S \to \gamma\gamma$ decay as well. The corresponding matrix element equals

$$M_{\gamma\gamma} = \frac{\alpha}{3\pi}\frac{\lambda_T}{m_T}F(\beta)F_{\mu\nu}^{(1)}F_{\mu\nu}^{(2)} \cdot 3_\mathrm{c}Q_T^2, \tag{7}$$

where the factor 3_c corresponds to the three colors, and Q_T is the T-quark electric charge. For $\gamma\gamma$ width we get:

$$\Gamma_{S\to\gamma\gamma} = \left(\frac{\alpha}{3\pi}\right)^2 (3_\mathrm{c}Q_T^2)^2 \frac{m_S^3\lambda_T^2}{16\pi m_T^2}|F(\beta)|^2 \approx 22\text{ keV}, \tag{8}$$

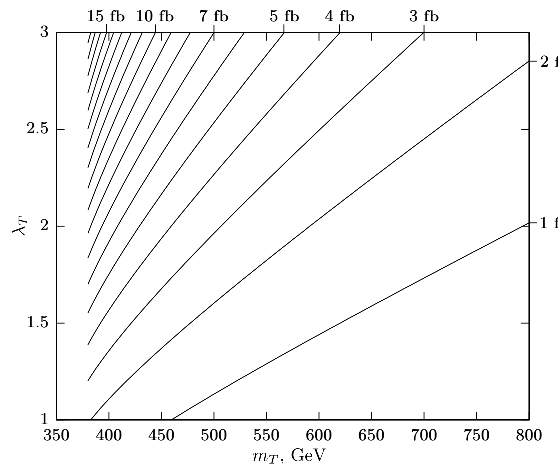

Figure 1. Contour plot of $\sigma_{pp\to SX} \cdot \mathrm{Br}(S \to \gamma\gamma)$.

$$\mathrm{Br}(S \to \gamma\gamma) \approx \left(\frac{\alpha}{\alpha_s}\right)^2 \frac{(3_\mathrm{c} Q_T^2)^2}{2} \approx 0.0070, \tag{9}$$

where we substituted $Q_T = 2/3$ and $\alpha = 1/125$.[1] Finally, we obtain:

$$\sigma_{pp\to SX} \cdot \mathrm{Br}(S \to \gamma\gamma) \approx 0.28 \text{ fb}. \tag{10}$$

Experimental data provides a value approximately 36 times larger:

$$[\sigma_{pp\to SX} \cdot \mathrm{Br}(S \to \gamma\gamma)]_{\mathrm{exp}} \approx 10 \text{ fb}. \tag{11}$$

This value follows from the the fact that both collaborations see about 15 events with 3 fb^{-1} luminosity collected by at 13 TeV and effectivity of $\gamma\gamma$ registration $\varepsilon \approx 0.5$ [1].

In order to reproduce experimental result (11) we should suppose that six T-quarks exist. In this case $\mathrm{Br}(S \to \gamma\gamma)$ remains the same, while the cross section of S production should be multiplied by the same factor 36, and (11) is reproduced.[2]

However, unappealing multiplication of the number of T-quarks can be avoided by diminishing T-quark mass and increasing the value of λ_T. The experimental result is reproduced for $m_T = 400$ GeV and $\lambda_T = 2.5$.[3] Curves of constant $\sigma_{pp\to SX} \cdot \mathrm{Br}(S \to \gamma\gamma)$ are shown in Figure 1 on (λ_T, m_T) plot.

In the rest of this section we consider the model with one additional quark T and $m_T = 400$ GeV, $\lambda_T = 2.5$. As it was shown above, this model can explain the diphoton excess but let us check that other existing bounds are not violated.

It is natural to suppose that T-quark mixes with u-, c-, and t-quark which makes it unstable. To avoid LHC Run 1 bounds on m_T following from the search of the decays $T \to Wb$, $T \to Zt$ and $T \to Ht$ [8–10] which exclude T-quark with mass below 700 GeV, we suppose that $T - t$ mixture is

[1] Fine structure constant is substituted by its running value at $q^2 = m_S^2$.

[2] The experimental result (11) will be reproduced if at 1 TeV scale we have a "mirror image" of the Standard Model with three vector-like generations.

[3] As far as $\lambda_T^2/4\pi$ is a parameter of perturbation theory, this value of λ_T is close to the maximum allowed value in order for the perturbation theory to make sense.

small, and T-quark mixing with u- and c-quarks dominates [11]. Though since we want the mass of T-quark to be just above the threshold of $S \to TT$ decay the mixing with the first two generations should not be too large in order to prevent the diminishing of $\mathrm{Br}(S \to \gamma\gamma)$ due to $S \to TT^* \to TWq$ decays.

Since at $\sqrt{s} = 8$ TeV the gluon-gluon luminosity is 4.6 times smaller that at $\sqrt{s} = 13$ TeV, the CMS bound from Run 1 $[\sigma_{pp\to SX}\mathrm{Br}(S \to \gamma\gamma)]_{8\ \mathrm{TeV}} < 1.5$ fb [12] is (almost) not violated.

Concerning S decays, let us note that the dominant $S \to gg$ decay is hidden by the two jets background produced by strong interactions. At 8 TeV LHC energy the following upper bound was obtained [13]:

$$[\sigma_{pp\to SX} \cdot \mathrm{Br}(S \to gg)]^{\mathrm{exp}}_{8\ \mathrm{TeV}} < 30\ \mathrm{pb}. \tag{12}$$

while in the considered model $[\sigma_{pp\to SX}]^{\mathrm{theor}}_{8\ \mathrm{TeV}} \approx 0.39$pb.

Three modes of S decays to neutral vector bosons do exist and have the following hierarchy $\Gamma_{S\to\gamma\gamma} : \Gamma_{S\to Z\gamma} : \Gamma_{S\to ZZ} = 1 : 2(s_W/c_W)^2 : (s_W/c_W)^4$, where $s_W(c_W)$ is the sine (cosine) of electroweak mixing angle (here we suppose that mixing of S with Higgs doublet is negligible). Thus if the existence of S will be confirmed by new data, $S \to \gamma Z$ and $S \to ZZ$ decays should be also looked for.

Scalar S can mix with the Standard Model Higgs boson due to renormalizable interaction term $\mu\Phi^\dagger\Phi S$, where Φ is the Higgs isodoublet. Such an extension of the Standard Model was studied in our recent paper [14]. Due to doublet admixture there are tree level decays $S \to WW$, ZZ, $t\bar{t}$ and hh, where h is the 125 GeV Higgs boson. According to Eqs. (16)–(20) from [14], the sum of these widths equals approximately $\sin^2\alpha \cdot m_S^3/8\pi v_\Phi^2 \approx \sin^2\alpha \cdot 300$ GeV, where α is the mixing angle, and $v_\Phi = 246$ GeV is the Higgs vev. Ratio of partial widths at small α is $\Gamma_{S\to WW} : \Gamma_{S\to ZZ} : \Gamma_{S\to hh} \approx 2 : 1 : 1$. As a result, S width grows and $\mathrm{Br}(S \to \gamma\gamma)$ diminishes correspondingly.

To reproduce experimental result (11) and in order not to violate bounds from searches in these modes, the mixing angle α should be small enough. For example, for $\sin\alpha < 1/150$ we obtain at most 12 MeV (or 11%) increase of the width of S, which is acceptable. It corresponds $|\mu| < 15$ GeV which is not unnaturally small.

Let us check if for such mixing angle $S \to ZZ$ decays (due to doublet admixture) do not exceed experimental bounds obtained at the LHC. In the considered model

$$[\sigma_{pp\to SX} \cdot \mathrm{Br}(S \to ZZ)]_{13\ \mathrm{TeV}} < 33\ \mathrm{fb}, \tag{13}$$

well below experimental upper bound which, according to Fig. 11 from [15], equals 4 fb$/(\mathrm{Br}(Z \to 4\ell))^2 = 400$ fb at 2σ (see also [16]).

For 8 TeV (taking into account energy dependence of the K-factor)

$$[\sigma_{pp\to SX} \cdot \mathrm{Br}(S \to ZZ)]_{8\ \mathrm{TeV}} < 9.0\ \mathrm{fb}, \tag{14}$$

while the experimental upper bound is 60 fb (Fig. 12 from [17]).

More stringent upper bound comes from the search of $S \to hh$ decays [18] and equals 40 fb, while in our case the cross section does not exceed 10 fb.

Let us say a few words about future prospects. If the existence of S will be confirmed with larger statistics at the LHC, then it can be studied at e^+e^--colliders as well. For the cross section of S production in photon fusion, according to [19, Eq. (48.47)], [20], we have:

$$\sigma_{ee\to eeS}(s) = \frac{8\alpha^2}{m_S^3}\Gamma_{S\to\gamma\gamma}\left[f\left(\frac{m_S^2}{s}\right)\left(\ln\left(\frac{m_T^2 s}{m_e^2 m_S^2}\right) - 1\right)^2 - \frac{1}{3}\ln^3\left(\frac{s}{m_S^2}\right)\right], \tag{15}$$

$$f(z) = \left(1 + \tfrac{1}{2}z\right)^2 \ln\tfrac{1}{z} - \tfrac{1}{2}(1-z)(3+z), \tag{16}$$

and $\Gamma_{S\to\gamma\gamma}$ is given in Eq. (8). At e^+e^- collider CLIC with $s = (3\text{ TeV})^2$ for $\lambda_T = 2.5$ and $m_T = 400$ GeV we obtain

$$\sigma^{\text{CLIC}}_{ee\to eeS} \approx 0.46\text{ fb}. \tag{17}$$

With projected CLIC luminosity $L = 6\cdot 10^{34}/(\text{cm}^2\cdot\text{sec})$ [19, p. 393], during one accelerator year ($t = 10^7$ sec) about 300 S resonances should be produced.

3 Leptophilic S

S production in $\gamma\gamma$ fusion will be analyzed in this section (see also [21–23]).

Let us suppose that heavy leptons L_i which couple to S have electric charges Q_L, and there are N such degenerate leptons. The lagrangian is similar to that of the heavy quarks case (1):

$$\Delta\mathcal{L} = \tfrac{1}{2}(\partial_\mu S)^2 - \tfrac{1}{2}m_S^2 S^2 + \bar{L}_i\gamma_\mu(\partial_\mu - ig'\tfrac{Y_L}{2}B_\mu)L_i + m_L\bar{L}_iL_i + \lambda_L\bar{L}_iL_iS, \tag{18}$$

where we assume equal lepton masses and S couplings. For $S\to\gamma\gamma$ width we obtain:

$$\Gamma_{S\to\gamma\gamma} = \left(\frac{\alpha}{3\pi}\right)^2 (NQ_L^2)^2 \frac{m_S^3\lambda_L^2}{16\pi m_L^2}|F(\beta)|^2,\ \beta = \left(\frac{2m_L}{m_S}\right)^2. \tag{19}$$

Production of S at the LHC occurs through fusion of two virtual photons emitted by quarks which reside in the colliding protons. Let us estimate the production cross section. For the partonic cross section we get:

$$\sigma^{(\gamma\gamma)}_{q_1q_2\to q_1q_2S}(\hat{s}) = \frac{8\alpha^2}{m_S^3}e_1^2e_2^2\,\Gamma_{S\to\gamma\gamma}\left[f\left(\frac{m_S^2}{\hat{s}}\right)\left(\ln\left(\frac{m_L^2\hat{s}}{\Lambda^2_{\text{QCD}}m_S^2}\right)-1\right)^2 - \frac{1}{3}\ln^3\left(\frac{\hat{s}}{m_S^2}\right)\right], \tag{20}$$

where e_1, e_2 are charges of the quarks, $\hat{s} = x_1x_2s \equiv \tau s$, and $f(z)$ is given by (16). We should multiply (20) by PDFs and integrate over x_1 and x_2:

$$\sigma^{(\gamma\gamma)}_{pp\to SX}(s) = \sum_{q_1,q_2}\int\limits_{m_S^2/s}^{1}\sigma^{(\gamma\gamma)}_{q_1q_2\to q_1q_2S}(\tau s)d\tau\cdot s\cdot\frac{dL_{q_1q_2}}{d\hat{s}}(Q^2,\tau). \tag{21}$$

$$\frac{dL_{q_1q_2}}{d\hat{s}}(Q^2,\tau) = \frac{1}{s}\int\limits_{\ln\sqrt{\tau}}^{-\ln\sqrt{\tau}} q_1(x_1,Q^2)q_2(x_2,Q^2)dy, \tag{22}$$

$x_1 = \sqrt{\tau}e^y$, $x_2 = \sqrt{\tau}e^{-y}$. We take $Q^2 = m_S^2$ and use PDFs from [4].

Cross sections in the case of one heavy lepton with charge $Q_L = 1$, Yukawa coupling constant $\lambda_L = 2$ and mass $m_L = 400$ GeV are shown in Table 1. For $\Lambda_{\text{QCD}} = 300$ MeV and $\sqrt{s} = 13$ TeV we get $\sigma^{(\gamma\gamma)}_{pp\to SX} \approx 11$ ab,[4] while the experimental result (11) is three orders of magnitude larger. We come to the conclusion that $\sum NQ_L^2 \approx 30$ is needed: we need either 30 leptons with unit charges, or one lepton with charge 6, or several multicharged leptons.[5]

[4] According to Eq. (12) from the recent paper [24], this cross section equals 25 ab.

[5] If $\sigma^{(\gamma\gamma)}_{pp\to SX} = 25$ ab, then 30 should be replaced with 20.

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Table 1. Cross sections (in ab) for double photon production in the leptophilic model for different values of $\Lambda_{\rm QCD}$ and proton collision energies.

		$\Lambda_{\rm QCD}$, GeV		
		0.1	0.3	1.0
$\sqrt{s}$, TeV	7	2.5	1.9	1.3
	8	3.8	2.9	2.0
	13	15	11	7.8

It is natural to suppose that leptons with charge one mix with the Standard Model leptons and become unstable. Search for such particles was performed at the LHC, and the lower bound $m_L >$ 170 GeV was obtained [25]. See also [26], where bounds on masses and mixings of L are discussed. For masses above 200 GeV the existence of L is still relatively unconstrained.

Cross section for quasielastic S production can be estimated with the help of the following equation:

$$\sigma_{pp\to ppS} = \frac{8\alpha^2}{m_S^3}\Gamma_{S\to\gamma\gamma}\left[f\left(\frac{m_S^2}{s}\right)\left(\ln\left(\frac{s}{m_S^2}\right)-1\right)^2 - \frac{1}{3}\ln^3\left(\frac{s}{m_S^2}\right)\right]. \tag{23}$$

For $\sqrt{s} = 13$ TeV, $\lambda_L = 2$ and $m_L = 400$ GeV it equals 4.1 ab.[6]

4 Conclusions

We analyze the possibility that the enhancement at 750 GeV diphoton invariant mass observed by ATLAS and CMS is due to decays of a new scalar S. We found that production of S in gluon fusion in a minimal model with one additional heavy Dirac quark T can have value of $\sigma_{pp\to SX}\cdot{\rm Br}(S\to\gamma\gamma)$ compatible with data. An upper bound on the mixing of S with $h(125)$ is obtained. If heavy leptons L are introduced instead of T, then S can be produced at LHC in photon fusion, however, in order to reproduce experimental data many leptons L_i are needed and/or they should be multicharged.

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