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 $\sigma_{pp\rightarrow S}\cdot Br(S \rightarrow \gamma\gamma)$.

1 Introduction

ATLAS and CMS collaborations recently announced a small enhancement over smooth background of two photon events with invariant mass 750 GeV \cite{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 $Br(S \rightarrow \gamma\gamma)$ reduces significantly which makes $S \rightarrow \gamma\gamma$ 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 $SU(2)_L$ 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 $\lambda_T^i$ and $\lambda_L^i$ correspondingly.

This talk is based on the paper \cite{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:

$$\Delta L = \frac{1}{2}(\partial_{\mu}S)^2 - \frac{1}{2}m_S^2S^2 + \bar{T}\gamma_{\mu}(\partial_{\mu} - \frac{i}{2}g_{\lambda_{i}}A_{\mu}^{\lambda_{i}} - i\g_{V}^{\lambda_{i}}B_{\mu})T + m_T\bar{T}T + \lambda_{T}\bar{T}TS,$$  \hspace{1cm} (1)

where $A_{\mu}^{\lambda_{i}}$ and $B_{\mu}$ are gluon and $U(1)$ gauge fields respectively, and $\lambda_{i}$ are Gell-Mann matrices. $S$ coupling with gluons is generated by the $T$-quark loop:

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

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

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

$$\sigma_{pp \to SX} = \frac{\alpha_s^2}{576\pi} \left(\frac{\lambda_T}{m_T}\right)^2 |F(\beta)|^2 m_S^2 \left|\frac{dL_{gg}}{d\hat{s}}\right|_{\hat{s} = m_S^2},$$  \hspace{1cm} (4)

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

$$\frac{dL_{gg}}{d\hat{s}} = \frac{1}{s} \int_{-\ln \sqrt{\hat{s}}}^{\ln \sqrt{\hat{s}}}(\sqrt{\tau_0}e^y, Q^2)g(\sqrt{\tau_0}e^{-y}, Q^2)dy,$$  \hspace{1cm} (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 $\sqrt{\hat{s}} = 750 \text{ GeV}, \sqrt{s} = 13 \text{ TeV}$, we get $dL_{gg}/d\hat{s} \approx 4.0 \text{ nb}, m_S^2dL_{gg}/d\hat{s} \approx (1/0.69 \text{ nb}) \cdot 4.0 \text{ nb} \approx 5.8$. 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 $\sqrt{\hat{s}} = 13 \text{ TeV}$, 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 $\sigma_{pp \to SX} \approx 41 \text{ fb}$, which should be multiplied by $\text{Br}(S \to \gamma\gamma)$ 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:

$$\Gamma_{S \to gg} = \left(\frac{\alpha_s}{6\pi}\right)^2 \cdot 8 \frac{m_S^3\lambda_T^2}{16\pi m_T^2}|F(\beta)|^2 \approx 3.1 \text{ MeV}.\hspace{1cm} (6)$$

Thus for the models we consider, the width of $S$ should be much smaller than $45 \text{ GeV}$ 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

$$M_{\gamma\gamma} = \frac{\alpha}{3\pi m_T} F(\beta) f^{(1)}_{\mu\nu} f^{(2)}_{\mu\nu} \cdot 3c Q_T^2,$$  \hspace{1cm} (7)

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

$$\Gamma_{S \to \gamma\gamma} = \left(\frac{\alpha}{3\pi}\right)^2 (3c Q_T^2)^2 \frac{m_S^3\lambda_T^2}{16\pi m_T^2}|F(\beta)|^2 \approx 22 \text{ keV},$$  \hspace{1cm} (8)
Figure 1. Contour plot of $\sigma_{pp \rightarrow SX} \cdot \text{Br}(S \rightarrow \gamma\gamma)$.

$$\text{Br}(S \rightarrow \gamma\gamma) \approx \left(\frac{\alpha}{\alpha_s}\right)^2 \frac{(3Q_T^2)^2}{2} \approx 0.0070,$$

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

$$\sigma_{pp \rightarrow SX} \cdot \text{Br}(S \rightarrow \gamma\gamma) \approx 0.28 \text{ fb}.$$

Experimental data provides a value approximately 36 times larger:

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

This value follows from the fact that both collaborations see about 15 events with $3 \text{ fb}^{-1}$ 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 Br$(S \rightarrow \gamma\gamma)$ remains the same, while the cross section of $S$ production should be multiplied by the same factor 36, and (11) is reproduced. However, unappealing multiplication of the number of $T$-quarks can be avoided by diminishing $T$-quark mass and increasing the value of $\lambda_T$. The experimental result is reproduced for $m_T = 400 \text{ GeV}$ and $\lambda_T = 2.5$. Curves of constant $\sigma_{pp \rightarrow SX} \cdot \text{Br}(S \rightarrow \gamma\gamma)$ are shown in Figure 1 on $(\lambda_T, m_T)$ plot.

In the rest of this section we consider the model with one additional quark $T$ and $m_T = 400 \text{ GeV}$, $\lambda_T = 2.5$. 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 $T \rightarrow Wb$, $T \rightarrow Zt$ and $T \rightarrow Ht$ [8–10] which exclude $T$-quark with mass below 700 GeV, we suppose that $T-t$ mixture is

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

2The 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.

3As far as $\lambda_T^2/4\pi$ is a parameter of perturbation theory, this value of $\lambda_T$ 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 $S \rightarrow TT$ decay the mixing with the first two generations should not be too large in order to prevent the diminishing of $\text{Br}(S \rightarrow \gamma \gamma)$ due to $S \rightarrow TT^* \rightarrow TWq$ decays.

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

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

$$|\sigma_{pp\rightarrow SX} \cdot \text{Br}(S \rightarrow gg)|_{8 \text{ TeV}}^{\text{exp}} < 30 \text{ pb},$$

while in the considered model $|\sigma_{pp\rightarrow SX}|_{8 \text{ TeV}}^{\text{theor}} \approx 0.39 \text{ pb}$.

Three modes of $S$ decays to neutral vector bosons do exist and have the following hierarchy $\Gamma_S \rightarrow \gamma \gamma : \Gamma_S \rightarrow ZZ : \Gamma_S \rightarrow TWq = 1 : 2 (s_W/c_W)^2 : (s_W/c_W)^4$, where $\Gamma_S$ 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, $S \rightarrow \gamma Z$ and $S \rightarrow ZZ$ 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 $\Phi$ 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 $S \rightarrow WW, ZZ, t\bar{t}$ and $hh$, where $h$ is the 125 GeV Higgs boson. According to Eqs. (16)–(20) from [14], the sum of these widths equals approximately $\sin^2 \alpha \cdot m_S^2/8\pi v^2_\Phi \approx \sin^2 \alpha \cdot 300 \text{ GeV}$, where $\alpha$ is the mixing angle, and $v_\Phi = 246 \text{ GeV}$ is the Higgs vev. Ratio of partial widths at small $\alpha$ is $\Gamma_S \rightarrow WW : \Gamma_S \rightarrow ZZ : \Gamma_S \rightarrow hh \approx 2 : 1 : 1$. As a result, $S$ width grows and $\text{Br}(S \rightarrow \gamma \gamma)$ diminishes correspondingly.

To reproduce experimental result (11) and in order not to violate bounds from searches in these modes, the mixing angle $\alpha$ 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 $|\mu| < 15 \text{ GeV}$ which is not unnaturally small.

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

$$|\sigma_{pp\rightarrow SX} \cdot \text{Br}(S \rightarrow ZZ)|_{13 \text{ TeV}} < 33 \text{ fb},$$

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

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

$$|\sigma_{pp\rightarrow SX} \cdot \text{Br}(S \rightarrow ZZ)|_{8 \text{ TeV}} < 9.0 \text{ fb},$$

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

More stringent upper bound comes from the search of $S \rightarrow hh$ 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:

$$\sigma_{ee\rightarrow ee5}(s) = \frac{8\alpha^2 m_s^2}{m_S^2} \Gamma_{S\rightarrow \gamma\gamma} \left[ f\left(\frac{m_S^2}{s}\right) \ln\left(\frac{m_S^2}{m_S^2 m_S^2}\right) - 1 \right] - \frac{1}{3} \ln^3 \left(\frac{s}{m_S^2}\right),$$

(15)
\begin{equation}
    f(z) = \left(1 + \frac{1}{2z}\right)^2 \ln \frac{1}{z} - \frac{1}{2}(1-z)(3+z),
\end{equation}
and $\Gamma_{S\rightarrow\gamma\gamma}$ is given in Eq. (8). At $e^+e^-$ collider CLIC with $s = (3 \text{ TeV})^2$ for $\lambda_F = 2.5$ and $m_T = 400 \text{ GeV}$ we obtain
\begin{equation}
    \sigma^{\text{CLIC}}_{ee\rightarrow eee} \approx 0.46 \text{ fb}.
\end{equation}
With projected CLIC luminosity $L = 6 \cdot 10^{34} / (\text{cm}^2 \cdot \text{sec})$ [19, p. 393], during one accelerator year ($t = 10^7 \text{ sec}$) 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):
\begin{equation}
    \Delta \mathcal{L} = \frac{1}{2}(\partial_{\mu}S)^2 - \frac{1}{2}m_S^2 S^2 + \bar{L}_i \gamma_{\mu}(\partial_{\mu} - ig'\frac{Y}{2}B_{\mu})L_i + m_L \bar{L}_i L_i + \lambda_L \bar{L}_i L_i S,
\end{equation}
where we assume equal lepton masses and $S$ couplings. For $S \rightarrow \gamma\gamma$ width we obtain:
\begin{equation}
    \Gamma_{S\rightarrow\gamma\gamma} = \left(\frac{\alpha}{3\pi}\right)^2 (NQ_L^2)^2 \frac{m_L^2}{16\pi m_S^2} |F(\beta)|^2, \quad \beta = \left(\frac{2m_L}{m_S}\right)^2.
\end{equation}
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:
\begin{equation}
    \sigma_{q_1 q_2 \rightarrow q_1 q_2 S}(s) = \frac{8\alpha^2}{m_S^2} \epsilon_1^2 \epsilon_2^2 \Gamma_{S\rightarrow\gamma\gamma} \left[ f \left( \frac{m_S^2}{\hat{s}} \right) \left( \ln \left( \frac{m_L^2}{\Lambda^2_{\text{QCD}} m_S^2} \right) - 1 \right) - \frac{1}{3} \ln^3 \left( \frac{\hat{s}}{m_S^2} \right) \right],
\end{equation}
where $e_1, e_2$ are charges of the quarks, $\hat{s} = x_1 x_2 s \equiv \tau s$, and $f(z)$ is given by (16). We should multiply (20) by PDFs and integrate over $x_1$ and $x_2$:
\begin{equation}
    \sigma_{pp \rightarrow SX}(s) = \sum_{q_1 q_2} \frac{1}{m_S^2/s} \int_{m_S^2/s}^{1} \sigma_{q_1 q_2 \rightarrow q_1 q_2 S}(\tau s) d\tau \cdot s \cdot \frac{dL_{q_1 q_2}}{d\hat{s}}(Q^2, \tau),
\end{equation}
\begin{equation}
    \frac{dL_{q_1 q_2}}{d\hat{s}}(Q^2, \tau) = \frac{1}{s} \int_{\ln \sqrt{\tau}}^{\ln \sqrt{\tau}} q_1(x_1, Q^2) q_2(x_2, Q^2) dy,
\end{equation}
$x_1 = \sqrt{\tau} e^{i\phi}, x_2 = \sqrt{\tau} e^{-i\phi}$. 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 $m_L = 400 \text{ GeV}$ are shown in Table 1. For $\Lambda_{\text{QCD}} = 300 \text{ MeV}$ and $\sqrt{s} = 13 \text{ TeV}$ we get $\sigma_{pp \rightarrow SX}(s) \approx 11 \text{ ab}$, 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.\footnote{According to Eq. (12) from the recent paper [24], this cross section equals 25 ab.}

\footnote{If $\sigma_{pp \rightarrow SX} = 25 \text{ ab}$, then 30 should be replaced with 20.}
Table 1. Cross sections (in ab) for double photon production in the leptophilic model for different values of $\Lambda_{\text{QCD}}$ and proton collision energies.

<table>
<thead>
<tr>
<th>$\Lambda_{\text{QCD}}$, GeV</th>
<th>0.1</th>
<th>0.3</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$, TeV</td>
<td>7</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td>2.5</td>
<td>1.9</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>3.8</td>
<td>2.9</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>11</td>
<td>7.8</td>
<td></td>
</tr>
</tbody>
</table>

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:

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

(23)

For $\sqrt{s} = 13$ TeV, $\lambda_L = 2$ and $m_L = 400$ GeV it equals 4.1 ab.\textsuperscript{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 $\sigma_{pp \rightarrow SX} \cdot \text{Br}(S \rightarrow \gamma\gamma)$ 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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References


\textsuperscript{6}According to Eq. (24) from [24], quasielastic cross section is two times smaller.
[16] Franceschini R. et. al., JHEP 1603, 144 (2016)