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New Physics at 1 TeV?

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If decays of a heavy particle S are responsible for the diphoton excess with invariant mass 750 GeV observed at the 13 TeV LHC run, it can be easily accomodated in the Standard Model. Two scenarios are considered: production in gluon fusion through a loop of heavy isosinglet quark(s) and production in 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 $\sigma_{pp\to SX}\cdot \mathrm{Br}(S\to\gamma\gamma)$.

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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 of Particle Physics is changed at one TeV scale, and we are witnessing the first sign of this change.

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 two photons, it should be an $SU(3)_\mathrm{c}$ singlet, and in pp-collisions at the LHC 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 particles propagating in the loops are heavy, and S decays to them are kinematically forbidden.[2)] Production cross section is evidently larger in the case of gluon fusion, however $S\to\gamma\gamma$ branching ratio is suppressed in this case since $S\to gg$ decay dominates.

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_T^i and λ_L^i correspondingly.

In Sect. 2 we will consider S production and decay in the model with extra heavy quark(s), in which gluon fusion dominates S production; in Sect. 3 we will consider the model with extra heavy lepton(s), where S production occur in photon fusion, and $S\to\gamma\gamma$ decay dominates.

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

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

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:

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

where $\beta = (2m_T/m_S)^2$,

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

and $F(\beta)\to 1$ for $m_T \gg m_S$.

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[2)] In the opposite case $\mathrm{Br}(S\to\gamma\gamma)$ reduces significantly which makes $S\to\gamma\gamma$ decays unobservable at the LHC.

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

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

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

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

$\tau_0 = \hat{s}/s$, $s = (13\ \text{TeV})^2$, and we use $Q^2 = m_S^2$. In Fig. 1 the corresponding Feynman diagram is shown. Integrating gluon distributions from [3] for $\sqrt{\hat{s}} = 750\,\text{GeV}$, $\sqrt{s} = 13\,\text{TeV}$, we get $dL_{gg}/d\hat{s} \approx 4.0\,\text{nb}$, $m_S^2\, dL_{gg}/d\hat{s} \approx$ $\approx (1/0.69\,\text{nb})\cdot 4.0\,\text{nb} \approx 5.8$. At $\sqrt{s} = 8\,\text{TeV}$ for $\sqrt{\hat{s}} =$ $= 750\,\text{GeV}$ the luminosity $dL_{gg}/d\hat{s}$, and therefore cross section (4), is 4.6 times smaller. 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 $\sqrt{s} = 13\,\text{TeV}$, according to [4] (see also Fig. 2 in [5]).

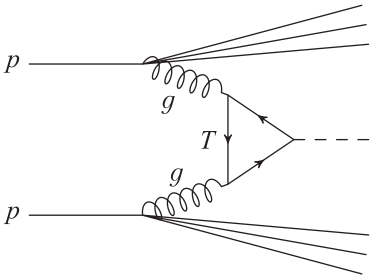

Fig. 1. Feynman diagram of S production

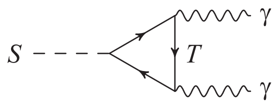

Fig. 2. Feynman diagram of $S \to \gamma\gamma$ decay

In this way for $m_T = m_S$ and $\lambda_T = 1$, substituting $\alpha_s(m_S) = 0.090$, we obtain:

$$\sigma_{pp\to SX} \approx 41\ \text{fb}, \quad (6)$$

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:

$$\Gamma_{S\to gg} = \left(\frac{\alpha_s}{6\pi}\right)^2 \cdot 8\frac{m_S^3\lambda_T^2}{16\pi m_T^2}|F(\beta)|^2 \approx 3.1\ \text{MeV}, \quad (7)$$

four orders of magnitude smaller than the 45 GeV width which (maybe) follows from the preliminary ATLAS data. Thus we conclude that for the models we consider, S width should be much smaller than 45 GeV. Let us note that CMS data prefer narrow S; see also [6].

T-quark loop contributes to $S \to \gamma\gamma$ decay as well (see Fig. 2). The corresponding matrix element equals

$$M_{\gamma\gamma} = \frac{\alpha}{3\pi}\frac{\lambda_T}{m_T}F(\beta)F_{\mu\nu}^{(1)}F_{\mu\nu}^{(2)}\cdot 3_\text{c}Q_T^2, \quad (8)$$

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:

$$\Gamma_{S\to\gamma\gamma} = \left(\frac{\alpha}{3\pi}\right)^2(3_\text{c}Q_T^2)^2\frac{m_S^3\lambda_T^2}{16\pi m_T^2}|F(\beta)|^2 \approx 22\ \text{keV}, \quad (9)$$

and

$$\text{Br}(S\to\gamma\gamma) \approx \left(\frac{\alpha}{\alpha_s}\right)^2\frac{(3_\text{c}Q_T^2)^2}{2} \approx 0.0070, \quad (10)$$

where we substituted $Q_T = 2/3$ and $\alpha = 1/125$.[3)] Finally, from (10) and (6) we obtain:

$$\sigma_{pp\to SX}\cdot\text{Br}(S\to\gamma\gamma) \approx 0.28\ \text{fb}. \quad (11)$$

Experimental data provides a value approximately 36 times larger:

$$[\sigma_{pp\to SX}\cdot\text{Br}(S\to\gamma\gamma)]_\text{exp} \approx 10\ \text{fb}, \quad (12)$$

since with 3 fb^{-1} luminosity collected by each collaboration at 13 TeV and effectivity of $\gamma\gamma$ registration $\varepsilon \approx 0.5$ [1] they see about 15 events each.

In order to reproduce experimental result (12) we should suppose that six T-quarks exist. In this case $\Gamma_{S\to gg} = 36\cdot 3.1\ \text{MeV} \approx 110\ \text{MeV}$, $\text{Br}(S\to\gamma\gamma)$ remains the same, while the cross section of S production (6) should be multiplied by the same factor 36, and (12) is reproduced.[4)]

However, unappealing multiplication of the number of T-quarks can be avoided. For $m_T = 400$ GeV we have $F(\beta) = 1.36$ and $\sigma_{pp\to SX}\cdot\text{Br}(S\to\gamma\gamma)$ is 5.7 times larger than what is given in (11). Thus for $\lambda_T = 2.5$ we reproduce the experimental number.[5)] In Fig. 3 isolines of the product $\sigma_{pp\to SX}\cdot\text{Br}(S\to\gamma\gamma)$ are shown on (λ_T, m_T) plot.

[3)] Fine structure constant should be substituted by its running value at $q^2 = m_S^2$, $\alpha(m_S^2) = 1/125$.

[4)] If at one TeV scale we have a "mirror image" of the Standard Model with three vector-like generations of quarks and leptons, then experimental result (12) will be reproduced.

[5)] 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.

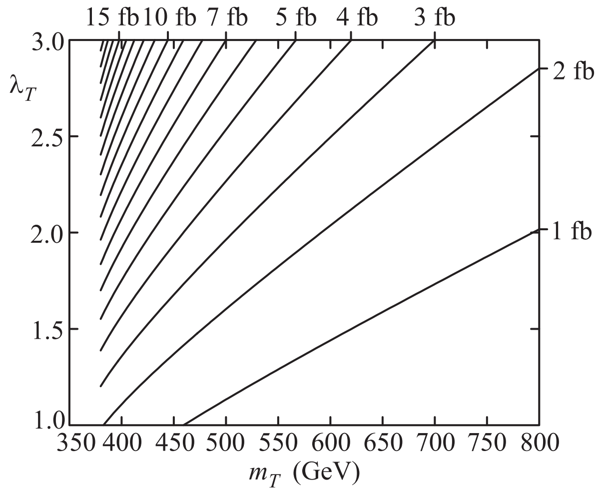

Fig. 3. Contour plot of $\sigma_{pp\to SX}\cdot \mathrm{Br}(S\to\gamma\gamma)$

In the following we consider the model with one additional quark T and

$$m_T = 400\ \mathrm{GeV},\ \ \lambda_T = 2.5. \qquad (13)$$

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 [7]. Doublet admixture in the 750 GeV boson wave function results in 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 [7], 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 boson vacuum expectation value. Ratio of partial widths at small α is

$$\Gamma_{S\to WW} : \Gamma_{S\to ZZ} : \Gamma_{S\to hh} \approx 2:1:1. \qquad (14)$$

As a result, S width grows and $\mathrm{Br}(S\to\gamma\gamma)$ diminishes correspondingly. Thus, experimental result (12) will not be reproduced. To reduce this effect we should make the mixing angle α 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. According to Eq. (7) from [7],

$$\sin\alpha \approx \frac{|\mu| v_\Phi}{m_S^2}, \qquad (15)$$

and it is less than 1/150 for $|\mu|$ below 15 GeV.

Let us check if $S\to ZZ$ decays do not exceed experimental bounds on their relative probability obtained at 13 and 8 TeV at the LHC. Since $\mathrm{Br}(S\to ZZ)$ is below $2.3\cdot 10^{-2}$, we obtain

$$[\sigma_{pp\to SX}\cdot \mathrm{Br}(S\to ZZ)]_{13\ \mathrm{TeV}} < 33\ \mathrm{fb}, \qquad (16)$$

well below experimental upper bound which, according to Fig. 11 from [8], equals 4 fb$/(\mathrm{Br}(Z\to 2\ell))^2 = 400$ fb at 2σ (see also [9]). Gluon-gluon luminosity is 4.6 times smaller at 8 TeV, so we get (taking into account energy dependence of the K-factor as well)

$$[\sigma_{pp\to SX}\cdot \mathrm{Br}(S\to ZZ)]_{8\ \mathrm{TeV}} < 9.0\ \mathrm{fb}, \qquad (17)$$

which should be compared with 60 fb experimental upper bound (Fig. 12 from [10]).

More stringent upper bound comes from the search of $S\to hh$ decays [11] and equals 40 fb, while in our case the cross section does not exceed 10 fb.

Since as it has just been written above, 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 [12]

$$[\sigma_{pp\to SX}\mathrm{Br}(S\to\gamma\gamma)]_{8\ \mathrm{TeV}} < 1.5\ \mathrm{fb} \qquad (18)$$

is (almost) not violated in the model considered.

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 $T\to Ht$ [13–15] which exclude T-quark with mass below 700 GeV, we suppose that $T - t$ mixture is small, and T-quark mixing with u- and c-quarks dominates. In this case bounds [13–15] are avoided [16].

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 [17]:

$$[\sigma_{pp\to SX}\cdot \mathrm{Br}(S\to gg)]^{\mathrm{exp}}_{8\ \mathrm{TeV}} < 30\ \mathrm{pb}. \qquad (19)$$

In our model $\mathrm{Br}(S\to gg)\approx 1$. From Eq. (4), using gluon-gluon luminosity at $\sqrt{s} = 8$ TeV, parameters from Eq. (13), and K-factor 2.5 [4, 5], we get

$$[\sigma_{pp\to SX}]^{\mathrm{theor}} \approx 0.39\ \mathrm{pb},\ \ \mathrm{Br}(S\to gg)\approx 1, \qquad (20)$$

two orders of magnitude smaller than the upper bound (19).

Three modes of S decays to neutral vector bosons do exist and have the following hierarchy:

$$\Gamma_{S\to\gamma\gamma} : \Gamma_{S\to Z\gamma} : \Gamma_{S\to ZZ} = 1 : 2(s_W/c_W)^2 : (s_W/c_W)^4, \qquad (21)$$

where s_W (c_W) is the sine (cosine) of electroweak mixing angle.[6)] Thus if $S\to\gamma\gamma$ decays will be observed in future Run 2 data, $S\to\gamma Z$ and $S\to ZZ$ decays should be also looked for.

[6)] In (21) we suppose that mixing of S with Higgs doublet is negligible; in the opposite case $\Gamma_{S\to ZZ}$ can exceed $\Gamma_{S\to\gamma\gamma}$.

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 two-photon S production in the reaction $e^+e^- \to e^+e^-S$, according to [18, Eq. (48.47)], [19], we have:

$$\sigma_{ee\to eeS}(s) = \frac{8\alpha^2}{m_S^3}\Gamma_{S\to\gamma\gamma} \times \\ \times \left[f\left(\frac{m_S^2}{s}\right)\left(\ln\left(\frac{m_T^2 s}{m_e^2 m_S^2}\right) - 1\right)^2 - \frac{1}{3}\ln^3\left(\frac{s}{m_S^2}\right)\right], \quad (22)$$

where

$$f(z) = \left(1+\frac{1}{2}z\right)^2 \ln\frac{1}{z} - \frac{1}{2}(1-z)(3+z), \quad (23)$$

and $\Gamma_{S\to\gamma\gamma}$ is given in Eq. (9). For e^+e^- collider CLIC with $s = (3\text{ TeV})^2$, substituting in Eqs. (9), (22) $\lambda_T = 2.5$, $m_T = 400$ GeV, $\alpha(m_S^2) = 1/125$, and $F(\beta) = 1.36$ we obtain:

$$\sigma^{\text{CLIC}}_{ee\to eeS} \approx 0.46\text{ fb}. \quad (24)$$

With projected CLIC luminosity $L = 6\cdot 10^{34}/(\text{cm}^2\cdot\text{sec})$ [18, 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 [20–22]).

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):

$$\Delta\mathcal{L} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 + \\ + \bar{L}_i\gamma_\mu\left(\partial_\mu - ig'\frac{Y_L}{2}B_\mu\right)L_i + m_L\bar{L}_iL_i + \lambda_L\bar{L}_iL_iS, \quad (25)$$

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

$$\Gamma_{S\to\gamma\gamma} = \left(\frac{\alpha}{3\pi}\right)^2 (NQ_L^2)^2 \frac{m_S^3\lambda_L^2}{16\pi m_L^2}|F(\beta)|^2,\ \beta = \left(\frac{2m_L}{m_S}\right)^2. \quad (26)$$

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:

$$\sigma^{(\gamma\gamma)}_{q_1q_2\to q_1q_2S}(\hat{s}) = \frac{8\alpha^2}{m_S^3}e_1^2e_2^2\Gamma_{S\to\gamma\gamma}\times \\ \times\left[f\left(\frac{m_S^2}{\hat{s}}\right)\left(\ln\left(\frac{m_L^2\hat{s}}{\Lambda^2_{\text{QCD}}m_S^2}\right)-1\right)^2 - \frac{1}{3}\ln^3\left(\frac{\hat{s}}{m_S^2}\right)\right], \quad (27)$$

where e_1 and e_2 are charges of the colliding quarks, $\hat{s} = x_1x_2s \equiv \tau s$ is the invariant mass of the colliding quarks, and $f(z)$ is given by (23). We should multiply (27) by quark distribution functions and integrate over x_1 and x_2:

$$\sigma^{(\gamma\gamma)}_{pp\to SX}(s) = \\ = \sum_{q_1,q_2}\int\limits_{m_S^2/s}^{1}\sigma^{(\gamma\gamma)}_{q_1q_2\to q_1q_2S}(\tau s)d\tau\cdot s\cdot\frac{dL_{q_1q_2}}{d\hat{s}}(Q^2,\tau), \quad (28)$$

where the sum should be performed over valence uu, ud, du, and dd quark collisions, and sea quarks should be taken into account as well.[7)] Quark luminosity equals:

$$\frac{dL_{q_1q_2}}{d\hat{s}}(Q^2,\tau) = \frac{1}{s}\int\limits_{\ln\sqrt{\tau}}^{-\ln\sqrt{\tau}} q_1(x_1,Q^2)q_2(x_2,Q^2)dy, \quad (29)$$

$x_1 = \sqrt{\tau}e^y$, $x_2 = \sqrt{\tau}e^{-y}$. We take $Q^2 = m_S^2$ and use quark distributions from [3]. Quark and gluon luminosity functions for $s = 13$ TeV and $s = 8$ TeV are shown in Fig. 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,[8)] while the experimental result (12) 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.[9)]

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 [24]. See also [25], 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:

$$\sigma_{pp\to ppS} = \frac{8\alpha^2}{m_S^3}\Gamma_{S\to\gamma\gamma}\times \\ \times\left[f\left(\frac{m_S^2}{s}\right)\left(\ln\left(\frac{s}{m_S^2}\right)-1\right)^2 - \frac{1}{3}\ln^3\left(\frac{s}{m_S^2}\right)\right]. \quad (30)$$

[7)] uu contribution constitutes 50% of the cross section at $\sqrt{s} = 13$ TeV with another 24% coming from ud and $\bar{u}u$.

[8)] According to Eq. (12) from the recent paper [23], this cross section equals 25 ab.

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

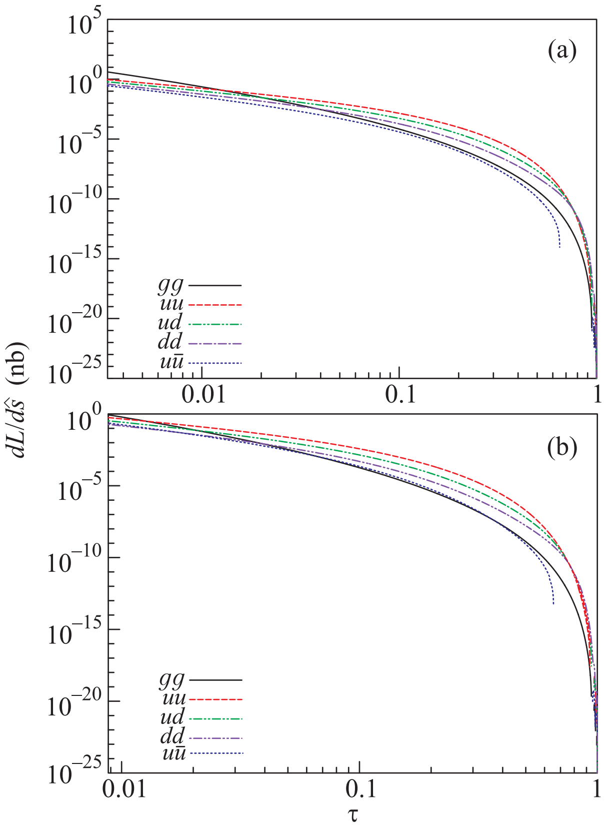

Fig. 4. (Color online) Luminosities (5), (29) for gluon-gluon, uu, ud, dd and $u\bar{u}$ collisions at $Q^2 = (750\text{ GeV})^2$. (a) – $\sqrt{s} = 13$ TeV. (b) – $\sqrt{s} = 8$ TeV

For $\sqrt{s} = 13$ TeV, $\lambda_L = 2$ and $m_L = 400$ GeV it equals 4.1 ab.[10)]

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

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

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 $\sigma_{pp\to SX} \cdot \text{Br}(S \to \gamma\gamma)$ 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. If the existence of S will be confirmed by future data then production of heavy vector-like quarks and/or leptons at the LHC should be looked for. The search for $S \to Z\gamma, ZZ, WW$ and hh would be also of great importance.

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[10)] According to Eq. (24) from [23], quasielastic cross section is two times smaller.

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