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New Physics beyond the 750 GeV diphotons events

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Abstract. the 750 GeV diphoton anomaly observed by ATLAS and CMS collaborations in 2015, and the models suggested by theorists to explain it. The talk has been presented in the special session devoted to this anomaly and possible (new) physics behind it. Since all the new physics models proposed by the beginning of the Conference predict many new particles accessible for direct study at present and next stages of LHC operation, which is very exciting, I chose the preposition "beyond" in the title.

1 Reports by ATLAS and CMS on December 15th, 2015

The first results obtained at the new for LHC center-of-mass energy of 13 TeV have been presented at CERN Seminar on December 15th [1]. The first talk was delivered by a CMS representative, who announces the results to be published in 6+17 new preprints based on the data collected from June 2015 to November 2015. Provided by the higher center-of-mass energy the data are of a special interest to the new physics models (17 new papers), where the direct production of new particles gets amplified as compared to the previous LHC run at 8 TeV. The most reliable new data sample refers to $L = 2.2\,\text{fb}^{-1}$ integral luminosity, and the models under discussion predict the production cross sections σ obeying the inequality

$$(\sigma \times L)_{13\,\text{TeV},\,2.2\,\text{fb}^{-1}} > (\sigma \times L)_{8\,\text{TeV},\,19.8\,\text{fb}^{-1}} \tag{1}$$

where integral luminosity $L = 19.8\,\text{fb}^{-1}$ stands for most reliable data collected at 8 TeV by CMS. Models with sufficiently heavy new particles may naturally satisfy (1). In particular, production cross section of gluons and squarks with masses of 1.5 TeV is enhanced at 13 TeV by a factor of 35 with respect to 8 TeV. CMS new data gave no any support of the previously announced signal at 1.8-2 TeV in diboson channels WW, WZ, ZZ with weak bosons reconstructed by jets. However, the CMS collaboration observed a new signal in $\gamma\gamma$ final state at about 750 GeV, while searching for massive gravitons expected within the Randall–Sundrum models of extra spatial dimensions. The anomaly is recognized only for photons collected in the barrel part of electromagnetic calorimeter: both photons carry significant transverse-to-beam momentum. This feature remain unexplained and may point at some errors in reconstruction, at a fake signal or at a real signal which confirmation requires more statistics.

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[1] CERN seminar, https://indico.cern.ch/event/442432/

The second talk was by ATLAS, which prepared 32 preprints with new results. This number noticeably exceeds that of the CMS, because of noticeably higher integral luminosity, 3.5-3.2 fb^{-1}, collected by ATLAS. The experiment CMS suffered from technical problems, one of the widely discussed is with magnetic field of the muon solenoid. At the new energy frontier ATLAS investigated 44 new signal regions in supersymmetric extensions of the Standard Model of particle physics (SM), extensions with heavy massive Z'- and W'-bosons, models with blackholes, models of dark matter, etc. The new data happened to be in some tension with previously found anomalies in diboson modes at 1.8-2 TeV and in the mode with missing energy and Z-boson decaying into electrons. A discouraging news was the lack of the Higgs bosons in the new data: a combined analysis of $\gamma\gamma$- and ZZ^*-modes revealed $1.4\,\sigma$ signal while $3.4\,\sigma$ was expected. At the same time ATLAS observed an anomaly in $\gamma\gamma$-channel with invariant mass of about $m_{\gamma\gamma} = 750$ GeV, which looked very much like the anomalous signal at CMS.

The CMS and ATLAS measurements of event distribution over the diphoton invariant mass $m_{\gamma\gamma}$ distribution are presented in Fig. 1. The signal in the ATLAS presentation (right panel) was much

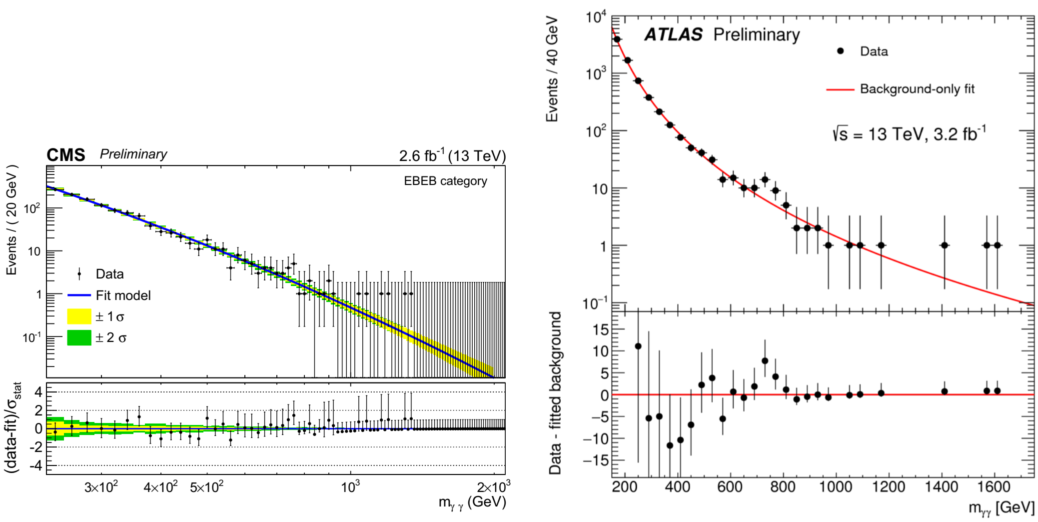

Figure 1. Diphoton invariant mass distribution measured by CMS [1] (left panel) and ATLAS [2] (right panel) collaborations. The anomalous signal was observed in both experiments at $m_{\gamma\gamma} \simeq 750$ GeV.

more pronounced than that of CMS (left panel), which might be caused by higher statistics (3.2 fb^{-1} vs 2.6 fb^{-1}). The ATLAS exhibited higher sensitivity to the signal. When fitted by zero-width resonance (i.e. when the diphoton invariant mass resolution $\Delta m_{\gamma\gamma}$ exceeds the resonance width $\Gamma_{\gamma\gamma}$), the local p-value characterizing the signal significance was $p = 3.6\,\sigma$. It became $3.9\,\sigma$ for wide-width approximation, the best fit value $\Gamma_{\gamma\gamma}/m_{\gamma\gamma} \approx 0.06$ corresponds to $\Gamma_{\gamma\gamma} \approx 46$ GeV. Thus, the data slightly favored the wide resonance. Note, that the p-values get dropped to 2-2.3 σ, respectively, when look elsewhere effect is properly accounted for. The penalty is taken for searching over 0.2-2 TeV diphoton invariant mass interval and also for scanning over the resonance width at $\Gamma_{\gamma\gamma}/m_{\gamma\gamma} < 0.1$. The signal significance of CMS signal was even lower ($3.0\,\sigma$ turned into $1.7\,\sigma$) but the fact that both experiment point at the same mass $m_{\gamma\gamma} \simeq 750$ GeV was reassuring.

2 Presented this Spring results (13 TeV and 8 TeV)

Being inspired by these results both collaborations proceeded to elaborate on the data, and later, at the Moriond Conference[2], have presented the extended analyses. A significant improvement was achieved by CMS [3], which included the data with zero solenoid magnetic field. The problems with solenoid seemed absolutely irrelevant for photon reconstruction in the electromagnetic calorimeter. These new data added 0.6 fb^{-1} to the CMS data used in the preliminary analysis and allowed CMS to achieve the sensitivity in the diphoton mode similar to that of ATLAS. Both data sets exhibit the signal at about 750 GeV, while the absence of the anomalous events with one or both photons flying along the beam axis (and to be registered in the end-cup calorimeters) has been confirmed. As a result, the local p-value jumped up to 2.9(2.8) σ for spin-0(2) resonance; thus CMS 13 TeV data give no hint of the resonance spin. Further, CMS had analyzed the data of 8 TeV run where some indication of the signal was observed. The combined fit favors the narrow resonance $\Gamma/M_{\gamma\gamma} = 1.4 \times 10^{-4}$ with local p-value of 3.4 σ decreasing to 1.6 σ due to the look elsewhere effect.

It is instructive to compare these results with the preliminary results of the combined analysis also shown at the CERN Seminar in December. To illustrate the situation, I plot in Fig. 2 the results

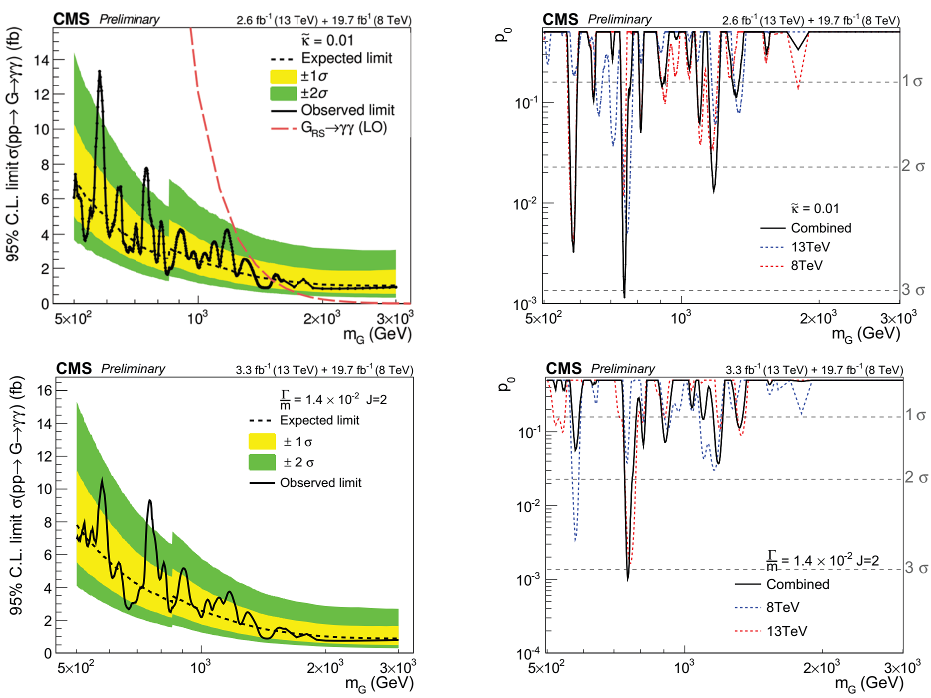

Figure 2. An example of combined CMS results: preliminary results presented at the CERN Seminar (top panel), results from the Moriond Conference (bottom panel).

obtained assuming $J = 2$ resonance (Randall–Sundrum models) with a particular width $\Gamma/M_{\gamma\gamma} = 1.4 \times 10^{-2}$ (it refers to $\bar{\kappa} = 0.01$ in the alternative notations). One can observe, first, that the new data of 0.6 fb^{-1} obtained with zero-magnetic field helped to get rid of the two peaks at $M_G \simeq 0.6$ TeV and $M_G \simeq 1.1$ TeV, seen in the combined 8+13 TeV data. Second, the preliminary analysis has been

[2] 51st Rencontres de Moriond, EW 2016, https://indico.in2p3.fr/event/12279/

Table 1. Summary of the diphoton anomaly [3, 4]; [QUARKS'16] indicate somewhat different numbers presented at the Conference by ATLAS and CMS speakers.

	ATLAS	CMS
p-values, loc(glob)	$3.9(2.3)\,\sigma$, $(2.0)\,\sigma$ [QUARKS'16]	$2.9(1.4)\,\sigma$, $(<1)\,\sigma$ [QUARKS'16]
resonance mass	$M_{\gamma\gamma} = 750\,\text{GeV}$	$M_{\gamma\gamma} = 760\,\text{GeV}$
resonance width	$\Gamma_{\gamma\gamma} \approx 45\,\text{GeV}$	$\Gamma_{\gamma\gamma} \approx 0\,\text{GeV}$
production at 13 TeV	$\sigma_{pp\to X} \times \text{Br}_{X\to\gamma\gamma} = (10 \pm 3)\,\text{fb}$	$\sigma_{pp\to X} \times \text{Br}_{X\to\gamma\gamma} = (3.7 \pm 1.4)\,\text{fb}$
integral luminosity	$3.3\,\text{fb}^{-1}$	$3.2\,\text{fb}^{-1}$
production at 8 TeV	$\sigma_{pp\to X} \times \text{Br}_{X\to\gamma\gamma} = (0.4 \pm 0.8)\,\text{fb}$	$\sigma_{pp\to X} \times \text{Br}_{X\to\gamma\gamma} = (0.5 \pm 0.6)\,\text{fb}$
integral luminosity	$20.3\,\text{fb}^{-1}$	$19.7\,\text{fb}^{-1}$
spin	certainly (?) not $J = 2$	no preference

checked and, apparently, some errors have been corrected including the data of 8 TeV run: compare the red dotted curve on the top right plot and blue dotted curve on the bottom right plot of Fig. 2 and find they are different.

ATLAS also added 8 TeV run data of $20.3\,\text{fb}^{-1}$ but arrived at qualitatively the opposite result [4]: the old data show (if any) a weaker signal. Namely, for the best-fit value $\Gamma/M_{\gamma\gamma} = 0.06$ and spin-0 resonance the data exhibit an excess of $1.9\,\sigma$, while one would expect a $1.2(2.1)\,\sigma$ stronger excess for the resonance produced in $gg(q\bar{q})$ scattering[3]. For spin-2 resonance no hint was recognized in the old data: the discrepancies between the observed signal end expected are $2.7(3.3)\,\sigma$ for the the gluon(quark) production channel.

The results of the both experiments are summarized in Table 1. One can see that, as compared to ATLAS, CMS measures 2.5 times smaller production cross section at 13 TeV, but observes a hint of signal at 8 TeV and has no preferences for the resonance spin.

It is worth to add that neither ATLAS no CMS reported any anomaly in $Z\gamma$, ZZ, WW, gg or hh channels in the interesting region of the corresponding invariant masses. Recall also, that the SM Higgs boson signal at 13 TeV is observed at much lower level than expected. Having all these in mind, still it is tempting to consider the anomaly observed by ATLAS and CMS as a hint of new physics: the direct production of the a heavy neutral boson. The numerous discrepancies between the anomalous results obtained at different energies and reported by different collaborations may be simply due to a lack of statistics.

3 Response from theorists

Theorists have immediately reacted to the announcement of the possible signal of new physics in $\gamma\gamma$-mode: 8 preprints have been submitted to the Cornell arXiv on the day of the CERN Seminar. By the date of this talk, May 31st, 365 preprint with references to the ATLAS preprint [2] have been issued in the arXiv. It is a desperate response of the overheated "gas of theorist" awaited for any signal of new physics in the LHC data. To say the truth, most probably several groups of LHC-related physicists were aware of details of the anomaly some time before the CERN Seminar. It would explain the submission of the very first paper [5] in 30 minutes after the Seminar. Likewise, the 8 papers of the first day after the Seminar are of 6, 23, 6, 19, 45, 6, 21, 3 pages, and it is rather difficult to believe that 20-page paper with a properly performed new physical analysis can be prepared in one evening.

[3] The difference is because of different evolution of gluon and quark parton distribution functions from 8 TeV to 13 TeV energy scale.

Anyway, the mostly cited paper (286 references[4] by May 31st) "What is the resonance at 750 GeV?" [7] was submitted on the first day and written by 10 authors; and 7 out of 10 are from CERN, which is also very elucidative. It is a paper of 45 pages, which "contains everything", that is all the information from experiments needed to theorist who is looking for a new beyond-the-SM (BSM) explanation of the observed anomaly. The violent reaction by theorists is naturally attributed to the fact that many well developed BSM theories contain (or can be straightforwardly supplemented with) a candidate for 750 GeV resonance. Indeed, the authors of 8 preprints issued (long) before the CERN Seminar later placed the references on the ATLAS and CMS results because the models they studied might be potentially relevant for the explanation of the anomalous events.

This activity have been recognized by a broader scientific community, and there is a paper [8] issued in March with predictions of time-evolution of the total number of papers referring to the ATLAS and CMS results, see Fig. 3. The paper presents a statistical analysis of the cumulative number

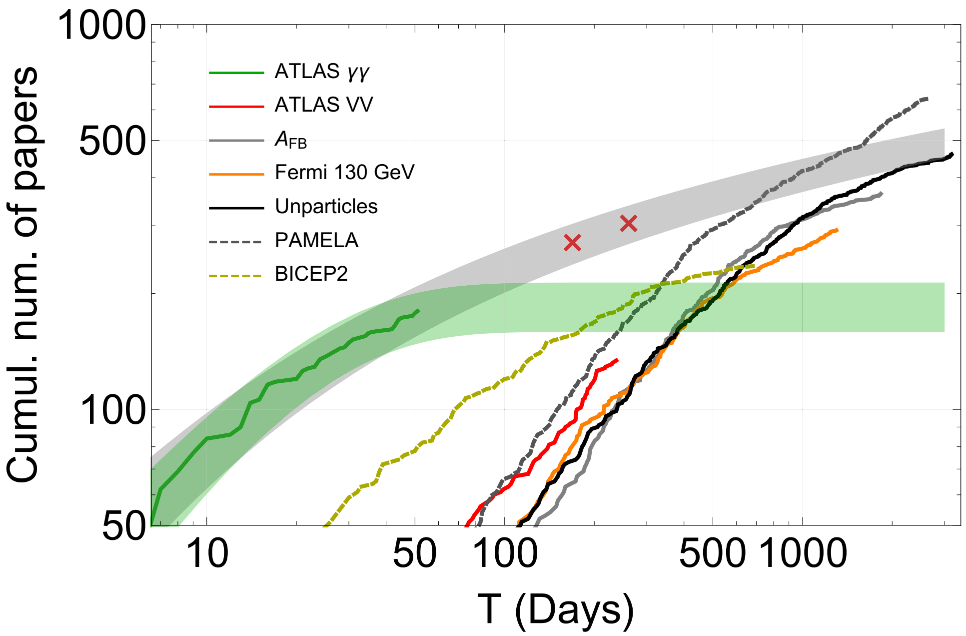

Figure 3. Time-distribution of the cumulative number of papers citing the papers which announced the particular anomalous results in particle physics, see Ref. [8] for details. Red crosses indicate the predictions for the papers referring to the ATLAS paper [2] about 750 GeV diphoton events.

of papers submitted in response to several well-known anomalies (relic gravity waves by BICEP2, cosmic positrons by PAMELA, γ-rays by Fermi, etc) which might point at the BSM physics but later have been explained within the SM. The conclusion was that the evolution follows the dilogarithm function and the number of papers referring to the ATLAS paper [2] must not exceed 310 by the 1st of June. From the number presented above one sees that the prediction was wrong: the theorist turned out to be more active and productive than expected. There are two reasons: reanalysis with new data presented at the Moriond Conference, and the fact that LHC just started to collect data promising to multiply the statistics by a factor of ten in a year.

[4]The next-to-it Ref. [6] was cited 208 times.

There are many reviews and books solely devoted to possible physics at LHC, mostly BSM physics. In particular, looking through the outlines of the books [9, 10], which may be treated as the LHC Bible and New Testament, respectively, one can find many hypothetical particles—nonstandard Higgs bosons, additional scalars, sgoldstino, sneutrino, technipions, massive gravitons—proposed in literature as the 750 GeV resonance, and many BSM theories—extra dimensions, supersymmetry, supersymmetry with R-parity violation, heavy quarks, dark matter, Z'- and W'-bosons, compositeness, heavy Majorana neutrino—which can be responsible for the resonance production at LHC. These are candidates for the soloist and its backing in this LHC play.

One can ask, given so many reliable candidates known for many years, did anybody predict a neutral particle of exactly 750 GeV mass? As far as I know, certainly not inside the particle physics community, though one may argue it can be related to the general scale of new physics taming the quadratic corrections to the Higgs boson mass squared. However, the almost exact number has been predicted by authors of the very popular cartoon series "Simpson" in 1998, when the main character Homer Simpson wrote a formula

$$M(H^0) = \pi \left(\frac{1}{137}\right)^8 \sqrt{\frac{hc}{G}}$$

presumably for the Higgs boson mass; here h, c and G stand for the Planck constant, speed of light in vacuum and the gravitational constant, respectively. Calculating this value one finds 775 GeV !! Hence, one can name the resonance under discussion as the Homer boson, which nicely fits to the notation H^0 from the cartoon. It is obviously an ad hoc prediction, however there are examples of predictions in particle physics which looked as ad hoc for decades. One is the "Greisen equation" in Cosmic ray physics dated to 1956,

$$\Pi(t, E_0/\epsilon_c) \approx \frac{0.31}{\sqrt{\beta_0}} \times \exp\left[t\left(1 - \frac{3}{2}\log s\right)\right],$$

which describes the number of particles in the shower at depth t, given the energy of initial high-energy cosmic ray particle E_0 and critical energy ϵ_c; here t is in units of the radiation depth, and I introduced the so-called shower age $s \equiv 3t/(t + 2\beta_0)$ and $\beta_0 = \log(E_0/\epsilon_c)$. Though the Greisen equation looks simple it works strikingly well. There was no deviation of this formula in the Greisen works or further papers, review, books on the subject, till 2007, when the detailed analysis has been performed in public [11].

4 Models, Problems, Predictions...

Parameters of any models proposed to explain the anomaly must be adjusted in a way to fit into the estimates of the resonance production cross section, mass and width shown in Table 1. The production channel and the decay branching ratio into two photons is not determined from the data, and the total width is either fixed (by ATLAS) or limited from above (by CMS). Even the spin of the resonance is not definitely fixed. Examples of the favored parameter space are presented in Fig. 4, assuming gluon fusion (left panel) and b-quark fusion (right panel) as the dominant production mechanisms.

The first definite statement about the resonance in diphoton mode is that it is either spin-0 or spin-2 (though the exotic Chern–Simons terms may make spin-1 viable as well). Now, from the ATLAS data spin-2 is disfavored; if not, the Kaluza–Klein gravitons may be suggested as possible candidates for the observed resonance. Since the new particle X is neutral, its interactions with gluons and photons are effective, like we have for the SM Higgs boson, $XG_{\mu\nu}G^{\mu\nu}$ and $XF_{\mu\nu}F^{\mu\nu}$, but then the new charged particles are needed, which couple both to X and the SM gauge bosons. They must be light and in a

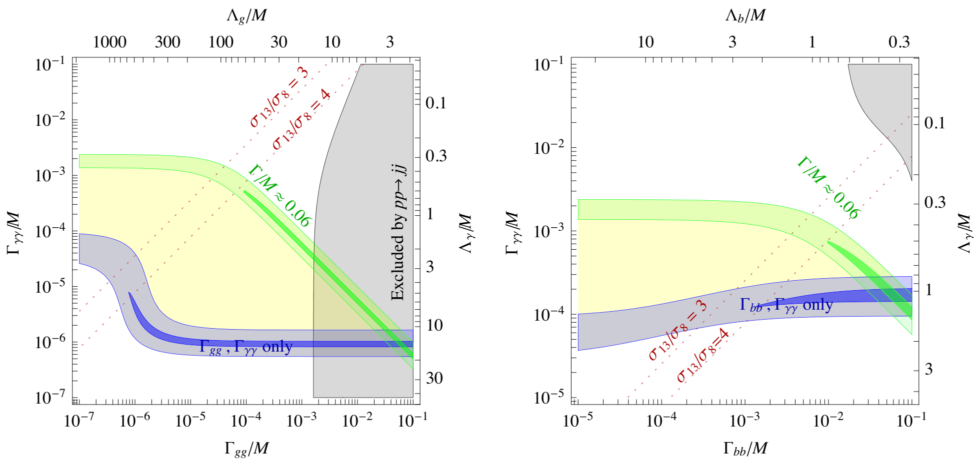

Figure 4. The regions in the resonance model parameter space (M is its mass, $\Gamma_{\gamma\gamma}$, Γ_{gg} and Γ_{bb} are its decay rates into two photons, two gluons and two b-quarks, respectively, and Λ_γ, Λ_g, Λ_b are new physics energy scales possibly responsible for the effective resonance coupling to photons, gluons and b-quarks, respectively). The resonance production goes through gg (left panel) or bb (right panel) fusions, correspondingly, see Ref. [7] for details. The gray regions are experimentally excluded, the green regions and blue regions show the models with wide and narrow resonances, in the latter case only $\gamma\gamma$ and the production channel contribute to the total resonance width. The red dotted lines are lines of the constant ratio of the production cross sections at 13 TeV and 8 TeV indicated by the label σ_{13}/σ_8. The green regions, blue regions and the yellow regions between the former two are favored by the observation of the 750 GeV resonance.

large number to ensure the sufficiently strong coupling constants in front of these interaction terms, because the constants scale with new particle masses M_f (say fermions) and numbers N_f as

$$\alpha_{Xgg} \propto \alpha_s \frac{N_f}{M_f}\,, \quad \alpha_{X\gamma\gamma} \propto \alpha \frac{e_f^2 N_f}{M_f}\,.$$

The most natural production mechanism is the gluon fusion; the quark fusion and photon fusion are rather difficult to accommodate, though in models with extra dimension Kaluza–Klein modes may help.

The simplest option for the new light particles is vector-like (to avoid gauge anomalies) quarks or leptons. Actually, the new bosons are somewhat preferred to new fermions, since they can make the Electroweak vacuum stable, which is needed for any high-energy scale inflation and especially for the Higgs-inflation. Note that mixing of the new resonance with the SM Higgs boson is rather constrained. Other options include sneutrinos in supersymmetric extensions with broken R-parity and sbino in models with Dirac-type bino.

The new boson may belong to the extended Higgs sector, it can be heavy CP-even H or axial A Higgs of 2 or 3 Higgs doublet models, H, A or additional singlet scalar n from (non)minimal supersymmetric extensions of the SM, extensions with inert Higgs doublets, scalar bosons from extended gauge sectors, like those in $U(1)_{B-L}$, $SU(2)_L \times SU(2)_R$, $SU(5)$, $SO(10)$, E_6, or those involved into seesaw type II mechanism, or radiation mechanism giving masses to active neutrinos etc. As a rule, always new charged particles are required.

The new resonance may have the Goldstone nature, like pseudoscalar mesons of QCD, and its decay into photons may originate from a quantum anomaly, like $\pi^0 \to \gamma\gamma$. Usually, it is not alone, but with mates (like charged pions in QCD), and examples are models with heavy axion, coloron, dilaton, radion, branons, sgoldstinos. Similar to other cases, in this type of models one must introduce new particles at ∼TeV scale.

In most models, given the $U(1)_Y$ gauge symmetry, one has to observe the resonance in γZ and ZZ channels as well, with the rate determined by the gauge symmetry. In many models the resonance must also show up in WW and gg channels.

There are many models nicely fitted to the resonance, if it is narrow, as CMS favors. The wide resonance is difficult to accommodate in many otherwise theoretically consistent and phenomenologically viable models. The width-to-mass ratio favored by ATLAS is very similar to what we have for many hadrons of QCD, which may suggest some technicolor model, or models with technicolor in a hidden sector. It might be that an invisible decay mode (e.g. into dark matter particles) dominates the resonance width, but the LHC searches for a single photon and a single jet events with missing energy severely constrain this option. Alternatively, one may consider decays of several different almost degenerate in mass particle mimicking the wide resonance. Other options are a three body decay into a photon pair and an elusive particle and decay into a couple of light pion-like states subsequently decaying into photon pairs with kinematics like two single photons.

5 Prospects

There are many models capable of explaining the diphoton anomaly. In most cases (with a few exceptions) these are extensions of earlier suggested BSM theories supplemented with new relatively light particles. All the models predict new charged with respect to the SM gauge group particles, light enough to be searched for at the LHC in the nearest future. Thus one must know by the end of the year, whether the Homer family will be invited to Stockholm. If the signal is real, the LHC physics must be fabulously rich, and we only start probing the heavy particle sector.

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