The Diphoton Anomaly

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Summary. — In December 2015, the ATLAS and CMS collaborations presented results from data taken at the LHC with pp collisions at the center of mass energy of $\sqrt{s} = 13$ TeV. In the search for resonances decaying into two photons, both experiments observed a tantalising excess of events at an invariant mass of the photon pair of 750 GeV. In this contribution, I will summarise some of the main phenomenological and theoretical aspects of this anomaly in terms of of New Physics.

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1. – The 750 GeV diphoton anomaly

On 15th December 2015, ATLAS and CMS summarised their physics results from the set of data accumulated in 2015 at the LHC at $\sqrt{s} = 13$ TeV. The experimental data have shown good agreement with the predictions of the Standard Model (SM) with the exception of a single analysis: the search for resonances decaying into a pair of photons in the final states. In particular, the ATLAS collaboration reported an excess of events in the invariant mass distribution of the diphoton pairs at about $M_{\gamma\gamma} = 750$ GeV with a local significance of 3.9σ [1]. A parametric fit of the decay width showed a mild preference for a large width of $\Gamma = 45$ GeV. Data from CMS [2] did not exclude the possibility of a new state (which in what follows will be denoted by S), obtaining a local statistical significance of the excess of 2.6σ with a slight preference for a narrow width ([1]). The background events are inferred and fitted in a data driven way, with an interpolating function that monotonically decreases with the invariant mass of the photon pairs: this is a motivated shape and the SM processes are not expected to produce peaks in this distribution.

([1]) Soon after this conference, new results have been released [3, 4, 5]. CMS included data taken with the magnet field turned off and both the collaborations revised and optimised their analysis (including those ones at $\sqrt{s} = 8$ TeV). As a result, the local significance of the diphoton anomaly has slightly increased.

Clearly the actual experimental situation does not allow the claim of a discovery of New Physics (NP) but the community hopes to get a final answer on this issue during the summer conferences or at the latest by the end of this year. It is fair to say that there is a logical possibility that this is just a statistical fluctuation. Despite (almost) all theoretical physicists agree that caution should be taken in this context, it has been difficult to resist the temptation of speculating about the possible interpretations of Physics Beyond SM (BSM), and indeed more than 300 papers have recently appeared on the arXiv.

Given these high number of references and ideas, I will present here only a partial and simplified summary of some phenomenologial and theoretical aspects of the diphton anomaly in terms of NP. I apologise to those who could not be quoted in this contribution.

2. – Phenomenological aspects

Assuming the presence of a BSM signal, the first step is to determine the cross section due to the putative new particle and also to check compatibility with similar analyses performed at 8 TeV. In this section, I will partially follow and quote results from [6]; however, various groups have performed analogous studies reaching similar conclusions, see for example [7, 8, 9].

The anomalous excess leads to the following estimates of the cross sections:

$$\sigma(pp \to \gamma\gamma) \approx \begin{cases} (0.4 \pm 0.8)\ \text{fb} & \text{ATLAS [10]} \quad \sqrt{s} = 8\ \text{TeV}, \\ (0.5 \pm 0.6)\ \text{fb} & \text{CMS [11]} \quad \sqrt{s} = 8\ \text{TeV}, \\ (10 \pm 3)\ \text{fb} & \text{ATLAS [1]} \quad \sqrt{s} = 13\ \text{TeV}, \\ (6 \pm 3)\ \text{fb} & \text{CMS [2]} \quad \sqrt{s} = 13\ \text{TeV}. \end{cases} \tag{1}$$

In order to address the issue of the consistency between the data at 8 and 13 TeV, it is not sufficient to compare the cross sections but an hypothesis on the possible production mechanism has to be done. Assuming that the new state S couples to the partons in the proton, the signal cross section can be rewritten as:

$$\sigma(pp \to S \to \gamma\gamma) = \frac{1}{\Gamma s}\left[\sum_P C_{P\overline{P}}(s)\Gamma(S \to P\overline{P})\right]\Gamma(S \to \gamma\gamma) \tag{2}$$

The factors $C_{P\overline{P}}(s)$ are the partonic integral at a given center of mass energy $\sqrt{s}$ and P is a parton confined in the proton. If we assume that the production cross section is dominated by a specific parton pair, we obtain the following gain factor $r_{P\overline{P}} \equiv \sigma_{13\ \text{TeV}}/\sigma_{8\ \text{TeV}}$:

$$\begin{array}{ccccccc} r_{b\bar{b}} & r_{c\bar{c}} & r_{s\bar{s}} & r_{d\bar{d}} & r_{u\bar{u}} & r_{gg} & r_{\gamma\gamma} \\ \hline 5.4 & 5.1 & 4.3 & 2.7 & 2.5 & 4.7 & 1.9 \end{array}\ . \tag{3}$$

Data at 8 TeV and 13 TeV are consistent at the the 2σ level if $r \gtrsim 3.5$. From this consideration we learn not only that the experimental results taken at different energies could be in agreement but also that some possible production mechanisms can be excluded. This indicates that, according to the data, production through heavy quarks and/or gluon fusion is preferred. This is useful information in order to construct explicit models of NP that address the explanation of the data.

I will now briefly consider gluon and bottom fusion.

final state f	σ at $\sqrt{s} = 8$ TeV observed	expected	σ at $\sqrt{s} = 13$ TeV observed	expected
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	< 5 fb	< 5 fb
$\tau^+\tau^-$	< 12 fb	< 15 fb	< 60 fb	< 67 fb
$Z\gamma$	< 11 fb	< 11 fb	< 28 fb	< 40 fb
ZZ	< 12 fb	< 20 fb	< 200 fb	< 220 fb
Zh	< 19 fb	< 28 fb	< 116 fb	< 116 fb
hh	< 39 fb	< 42 fb	< 120 fb	< 110 fb
W^+W^-	< 40 fb	< 70 fb	< 300 fb	< 300 fb
$t\bar{t}$	< 450 fb	< 600 fb		
invisible	< 0.8 pb	—	2.2 pb	1.8 pb
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb		
jj	$\lesssim 2.5$ pb	—		

TABLE I. – *Updated bounds at 95% confidence level on $\sigma(pp \to S \to f)$ cross sections for various decay channels f. These results are taken from [12].*

In the case of gluon fusion production, the anomalous events can be reproduced if:

$$\frac{\Gamma_{\gamma\gamma}}{M}\frac{\Gamma_{gg}}{M} \approx 1.1 \times 10^{-6}\frac{\Gamma}{M} \tag{4}$$

where $\Gamma_{\gamma\gamma} \equiv \Gamma(S \to \gamma\gamma)$, $\Gamma_{gg} \equiv \Gamma(S \to gg)$ and $M = 750$ GeV. In this case, in order to reproduce the large width hinted by ATLAS, more decays channels are required. Indeed, the case of large coupling to gluons leads to conflict with di-jets searches ($pp \to S \to jj$).

If the S particle is produced by b-quark fusion we have that:

$$\frac{\Gamma_{\gamma\gamma}}{M}\frac{\Gamma_{b\bar{b}}}{M} \approx 1.9 \times 10^{-4}\frac{\Gamma}{M} \tag{5}$$

In this case a large width can be obtained and can be saturated by the decay into bottom quarks $\Gamma_{b\bar{b}} \approx \Gamma \approx 45$ GeV.

If this particle exists, we will be interested not only in understanding its production mechanism(s) but also in finding all the accessible decay channels. Experimental searches at 8 TeV (but also at 13 TeV) did not show any significant deviation from the SM. This information can be used to set bounds on the partial decay width of S into specific final states, see Table I for a summary of the experimental bounds.

Particularly interesting decay channels for future searches at Run 2 are:

1. $S \to$ electroweak bosons.

   In the SM the electromagnetic gauge interaction $U(1)_Q$ is embedded in a non-trivial way into $SU(2)_L \times U(1)_Y$. This means that is very natural to expect the S particle to decay also in some other 2-body decay channels containing EW gauge bosons, in particular in W^+W^-, ZZ and $Z\gamma$. A possible measurement of one or more of these decays could be a crucial information to discriminate within different UV models. Despite it is quite expected to observe possible decays in these channels, it is fair to remark that there is no proof that guarantees an observation at the LHC ([2]).

2. $S \to t\bar{t}$.

   In various extensions of the SM, it is theoretically motivated to expect the NP to couple more strongly to the third family of quarks, and in particular to the top. This is the case in various strongly coupled extensions. The present experimental bounds on this channel are rather weak and a possible large width can be easily saturated by decays into this channel.

3. $S \to$ invisible.

   One the most clear experimental evidence of physics BSM is the presence of Dark Matter (DM) in the universe. In various BSM extensions the DM is produced thermally through the freeze-out mechanism. This means that the DM particles can annihilate into SM fermions, which implies that some interactions have to connect the SM sector to the DM one. Various authors suggested that the particle S could be the messenger between these 2 sectors [13, 14, 15, 16]. The S particle can decay into DM giving rise to invisible final state at the LHC. In this case, the bounds are very weak and a large width can be easily accommodated.

Before moving to explicit models, it is important to mention that in this section only the simplest kinematical topology for the process has been considered, that is a single resonance exchanged in the s-channel that directly decays into photons. There have been attempts to consider different topologies [6, 8, 17, 18, 19]. In addition, the new state S was assumed to be a Lorentz scalar but higher spin hypothesis have been considered as well, see for example [20].

3. – Weakly coupled extensions

The most popular idea used to explain the anomaly in renomarmazible models is to assume the presence of extra vector-like fields that carry electric and/or colour charges. These models allow for a Yukawa-like interaction of the scalar S with the new states and at the one-loop level the 750 GeV resonance is coupled to photons and to gluons.

As an example, I will consider the simple toy model introduced in [21]. Despite its simplicity, the toy model captures the main features of several proposals that have appeared in the literature. In a two-component notation for fermions, we introduce N_Q copies of neutral vector-like QCD triplets (Q_A, Q_A^c) as well as N_E copies of colorless vector-like fermions (E_B, E_B^c), singlet under $SU(2)_L$ and with hypercharge Y. We assume the theory to be invariant under a $SU(N_Q) \times SU(N_E)$ global symmetry. We assume also CP conservation in the NP sector, and we consider S to be a real pseudo-scalar field. The most general Lagrangian beyond the SM with the above assumed symmetries is given by:

$$\begin{aligned}\mathcal{L}_{\rm NP} &= iQ_A^\dagger \sigma^\mu D_\mu Q_A + iQ_A^{c\dagger}\sigma^\mu D_\mu Q_A^c + iL_B^\dagger \sigma^\mu D_\mu L_B + iL_B^{c\dagger}\sigma^\mu D_\mu L_B^c \\ &- (M_Q Q_A^c Q_A + M_E E_B^c E_B + iy_q Q_A^c Q_A S + iy_e E_B^c E_B S + \text{h.c.}) \\ &- \left(\frac{M^2}{2}S^2 + \frac{\lambda}{4!}S^4\right) .\end{aligned}$$

([2]) I thank David Marzocca for a useful discussion on this point.

Invariance under parity forces y_q and y_e to be real and is responsible also for the absence of linear and cubic terms in S in the potential. We are also omitting for simplicity the scalar quartic coupling $H^\dagger H S^2$. The induced widths from fermion loops are given by:

$$\Gamma(S \to gg) = M \frac{\alpha_3^2}{8\pi^3} N_Q^2 y_q^2 \tau_Q \left|\mathcal{P}(\tau_Q)\right|^2 , \tag{6}$$

$$\Gamma(S \to \gamma\gamma) = M \frac{\alpha^2}{16\pi^3} Y^4 N_E^2 y_e^2 \tau_E \left|\mathcal{P}(\tau_E)\right|^2 , \tag{7}$$

where $\tau_Q = 4M_Q^2/M^2$ and $\tau_E = 4M_E^2/M^2$ and the loop function is defined as:

$$\mathcal{P}(\tau) = \arctan^2(1/\sqrt{\tau - 1}) . \tag{8}$$

We take the values of mediator masses close to their expected experimental exclusion limit. In particular, we take $M_Q = 1$ TeV and $M_E = 400$ GeV. The decay widths normalized to the mass of the scalar are given by:

$$\frac{\Gamma\left(S \to gg\right)}{M} = 5.7 \cdot 10^{-6}\, y_q^2 N_Q^2 , \qquad \frac{\Gamma\left(S \to \gamma\gamma\right)}{M} = 1.1 \cdot 10^{-7}\, Y^4 y_e^2 N_E^2 , \tag{9}$$

In order to reproduced the excess of events at 750 GeV we need to satisfy Eq.(4). This can be easily done for a narrow width; however, a closer inspection of the diphoton rate reveals that weakly coupled models are disfavoured if the width is large. Indeed, in this case, we have that $\Gamma_{\gamma\gamma}/M \gtrsim 10^{-4}$, which implies $Y^4 y_e^2 N_E^2 \gtrsim 10^3$ and we conclude that we need to have large couplings and/or large multiplicity of states ending in a strongly couple regime for our parameters. This aspect is supported by various considerations based on the analysis of the RGE [21, 22, 23], perturbative unitarity [24, 25] and stability of the scalar potential [26].

I'll conclude this section commenting on the interpretation of the anomaly in the two most popular weakly coupled extensions of the SM: the two Higgs doublet model (2HDM) and the MSSM, see for example [27, 28, 29]. In their *minimal* versions, they cannot accommodate the data for the reasons reported below.

1. 2HDM

   Despite the model contains new neutral scalar states, a large rate in $\gamma\gamma$ cannot be accommodated (even for a narrow width). The reason is that the mediators required to generate couplings to photons are forced to be SM particles. In this case, S can decay into the same particles that are in the loop and a comparison between the loop induced rate to photons with the tree-level decay leads to conclude that this case is ruled out by direct searches. For a example, assuming that only the top contributes to the induced diphoton decay rate, we have that $\Gamma_{\gamma\gamma} \sim 10^{-5}\Gamma_{t\bar{t}}$, using Table I we can conclude that this is already excluded.

2. MSSM

   The Higgs sector of the MSSM is a special type of 2HDM, and we already now that this model cannot accommodate the data. Yet, the MSSM spectrum contains extra supersymmetric particles that can contribute to enhancing the rate in the loop. However, supersymmetry imposes restrictions to the structure of the interactions and the contribution to the diphoton rate is not enough to explain the data.

4. – Strongly coupled extensions

The difficulty in obtaining a sizeable decay rate $S \to \gamma\gamma$ from weakly coupled models led various authors to consider strongly coupled extensions of the SM, see for example [6, 30, 31, 32, 33, 34, 35]. In this case, the 750 GeV resonance S is a composite state. The most popular direction has been based on the idea of vector-like confinement [36]: the SM is extended by a new gauge sector that enters in a strongly coupled regime in the infrared and breaks spontaneously its global symmetry. This idea is common to technicolor theories with the difference that the Spontaneous Symmetry Breaking (SSB) pattern leaves the SM gauge symmetry unbroken. The leading order questions to address are: which kind of state S is in this framework, how to get a large decay rate in photons, and how to produce it at the LHC. If S is a pseudo-goldstone boson, it is natural to expect it to be among the lightest states; this could explain why S is the first state of the sector that showed up at the LHC. The large production cross section through gluon fusion and decay rate into photons can be easily obtained by carefully choosing the representations of the new fermions in the UV gauge theory so to generate the correct current anomalies. It is quite interesting to note that we are simply mimicking some aspects of QCD: indeed, SSB proceeds in a similar way, S is a goldstone boson like the neutral pion in QCD, and its decay into photons is due to an anomaly in complete analogy to $\pi^0 \to \gamma\gamma$. Other appealing aspects of these models are the absence of extra sources of flavour violation compared with the SM, the possibility to have various kinds of stable candidate that could play the role of the DM, and the possibility to obtain a large total decay width for S (for example, S could decay into lighter neutral goldstone states that escape direct detection at the LHC).

However, in these models there is no explanation on why a new gauge sector has to exist very close to the EW scale. Creating a link between the origin of the EW scale and that of the new dynamical scale is more challenging. Some attempts go in the direction of trying to find a larger global symmetry group that admits simultaneously the Higgs and the S as goldstone bosons in the coset space as in [37, 38]. Despite the low energy physics can be encoded in an elegant way through an effective field theory formalism, it is fair to say that complete explicit models in 4-dimensions are difficult to be constructed.

5. – Conclusions

The diphoton excess is definitely the most interesting anomaly observed so far at the LHC. If confirmed by further data, it is natural to expect the observation of the decay of S also into other EW gauge bosons. Another general expectation is the presence of extra electrically charged states (elementary or composite) that act as mediators to couple the neutral state to photons. With some luck, these states might be discovered soon with more data. Production mechanism, decays into other SM final states, etc. are model-dependent aspects and any phenomenological information will be crucial to reconstruct the right model behind this excess. In particular, a confirmation of the large width hinted by ATLAS would point towards strongly coupled extensions of the SM model.

In conclusion, we need more data to clarify the situation. In the most optimistic scenario, this state could lead us to major breakthroughs in our field, such as a possible solution (or a better understanding) of the naturalness problem of the EW scale, or a possible connection with the DM sector. On the other hand, the most pessimistic output from the next set of data could reveal that the diphoton excess is only a statistical fluctuation.

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