The Diphoton Anomaly as Nonlinear Optics Effect

Ervin Goldfain

Advanced Technology and Sensor Group, Welch Allyn Inc., Skaneateles Falls, NY 13153

Abstract

We speculate on the idea that the root cause of the recently reported diphoton excess at the Large Hadron Collider (LHC) is a *nonlinear quantum optics effect*. The effect is likely to arise from the strong coupling of photons to the sea of relativistic Coulomb charges carried by light quarks.

Key words: Diphoton excess, 750 GeV resonance, nonlinear optics, polaritons, optical parametric amplifier.

Both ATLAS and CMS collaborations at the LHC have recently reported an excess of diphoton events around the invariant mass of 750 GeV, with a local significance of 3.6σ and 2.6σ, respectively [1]. The *diphoton anomaly*, produced in the second run of the LHC at $\sqrt{s} = 13$ TeV, has instantly generated an overflow of hypothetical "Beyond the Standard Model" (BSM) explanations including, but not limited to, extended Higgs sectors, heavy axions, monojet signatures of Dark Matter, hidden valleys states, dibosons, KK gravitons, goldstinos, sbinos, three body decays, dilatons, scalars from gluon fusion, photon fusion, dark pions and so on [2-3].

Excluding the possibility of statistical fluctuations or unaccounted artifacts, here we explore a speculative scenario that does not necessarily require BSM physics. The idea is that the anomaly stems from a *nonlinear polarization* process. The polarization is induced in the "sea" of *u* and *d* quark charges embedded in the pair of colliding protons.

In particular, relativistic *pp* collisions transform outgoing photons into quasiparticles similar to the way polaritons arise in solid-state physics. The end result is that the system photon-relativistic "QCD matter" turns into an *optical parametric amplifier*.

The dynamics of quark interactions in *pp* collisions is likely to include, besides accelerated motion, random and sustained oscillations in both color and Coulomb charges. The possibility of frequent collisions among quarks and gluons at short distances suggest that the emitted dipole radiation, referred to as *pump mode*, may be regarded as a *quantum fluid* with collective type behavior [4-5]. Photon-photon interactions may be a likely outcome of this mechanism. Historically, Heisenberg and Euler, as well as Schwinger, were the first to show that quantum vacuum under the action of a constant electromagnetic field could behave as "matter", become nonlinearly polarized and bind photons to photons via virtual electron-positron pairs [6-8]. However, the cross-section for such processes is known to be exceedingly small to be detectable, unless the driving electromagnetic field is supplied by ultrahigh-power lasers [6-8]. By contrast, as the last few decades have indicated, *nonlinear polarization of optical media* is capable of delivering sizable photon-photon interactions. It is in these regimes that photons are strongly "dressed" with the electric dipoles of the medium giving rise to polaritons [4-5]. As it is known, the main ingredient of optical nonlinearity is the nonlinear dependence of the "matter" polarization on the applied electric field and is the source of several wave-mixing processes that couple different cavity modes and generates new frequency components.

A similar situation can likely occur in diphoton interactions with "QCD matter", under some extreme dynamic conditions involving relativistic motion and confinement. If the rotating-wave approximation holds well and if photon frequencies are sufficiently "detuned" from the resonant frequencies of quark charges, it can be shown that the diphoton potential in one-dimensional cavities assumes the form [4]

$$V^0 = -\frac{3\pi n_{NL}(\hbar\omega_{cav}^0)^2}{n_0\Delta} \tag{1}$$

in which n_{NL} is the nonlinear refractive index ($n_{eff} = n_0 + n_{NL}|E|^2$), E is the applied field, ω_0^{cav} is the frequency cutoff and Δ the cavity thickness

$$\omega_{cav}^0 = \frac{1}{n_0\Delta} \tag{2}$$

Substituting (2) in (1), shows that the magnitude of the diphoton potential scales linearly with the n_{NL} and with the inverse of the cubic power of cavity thickness (Δ^3). It follows that photon-photon coupling and photon blocking in steep potentials act as competing effects and suppression of outgoing photons is expected for vanishing Δ and moderate magnitudes of n_{NL}.

Following [9], an overly simplified picture of this process is as follows: Assume that the electromagnetic radiation emitted by moving quark charges has frequency ω_P and acts like an external pump mode. It interacts inside the nonlinear optical cavity with two modes at frequencies ω_1 and ω_2 summing up to the pump frequency ($\omega_P = \omega_1 + \omega_2$). Further assume that mode (1) represents the *signal photon* produced by all decay channels allowed by the Standard Model, and let mode (2) denote the fraction of pump photons leaking out of the optical cavity. The Hamiltonian describing the interaction is

$$H = \hbar\omega_1 a_1^+ a_1 + \hbar\omega_2 a_2^+ a_2 + i\hbar\chi(a_1^+ a_2^+ e^{-i\omega_P t} - a_1 a_2 e^{i\omega_P t}) \tag{3}$$

where $a_1(a_2)$ stands for the annihilation operator for the two modes. The coupling constant $\chi = O(n_{NL})$ depends on the second-order susceptibility of the cavity and the amplitude of the pump. The Heisenberg equations of motion derived from (1) are given by

$$\frac{da_1}{dt} = \chi a_2^+ \tag{4a}$$

$$\frac{da_2^+}{dt} = \chi a_1 \tag{4b}$$

leading to the following pair of solutions

$$a_1(t) = a_1 \cosh(\chi t) + a_2^+ \sinh(\chi t) \tag{5a}$$

$$a_2(t) = a_2 \cosh(\chi t) + a_1^+ \sinh(\chi t) \tag{5b}$$

If the system is initially in a coherent state described by $|\alpha_1\rangle, |\alpha_2\rangle$, the mean photon count in the signal mode at time t is

$$\langle n_1(t)\rangle = \langle \alpha_1, \alpha_2 | a_1^+(t) a_1(t) | \alpha_1, \alpha_2 \rangle = \left| \alpha_1 \cosh(\chi t) + \alpha_2^* \sinh(\chi t) \right|^2 + \sinh^2(\chi t) \tag{6}$$

The last term in (6) denotes the *amplification of vacuum fluctuations* since, even if the initial state for the two modes is the vacuum ($\alpha_1 = \alpha_2 = 0$), the mean photon count grows as $\sinh^2(\chi t)$ after a time lag t.

We close this brief note with the observation that the mechanism described here is fundamentally different from the proposed photon fusion process invoked in [10]. There, the diphoton excess requires introduction of a new scalar resonance, mostly coupled to electroweak gauge fields.

References

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