Diphoton Signatures from Heavy Axion Decays at the CERN Large Hadron Collider

DOI: 10.1103/PhysRevD.93.015017

Document Version
Final published version

Link to publication record in Manchester Research Explorer

Citation for published version (APA):

Published in:
Physical Review D (Particles, Fields, Gravitation and Cosmology)

Citing this paper
Please note that where the full-text provided on Manchester Research Explorer is the Author Accepted Manuscript or Proof version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version.

General rights
Copyright and moral rights for the publications made accessible in the Research Explorer are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Takedown policy
If you believe that this document breaches copyright please refer to the University of Manchester’s Takedown Procedures [http://man.ac.uk/04Y6Bo] or contact uml.scholarlycommunications@manchester.ac.uk providing relevant details, so we can investigate your claim.
Recently, the ATLAS and CMS collaborations have analyzed Run 2 LHC data gathered at center-of-mass energies of $\sqrt{s} = 13$ TeV. They reported an excess in the diphoton channel around an invariant mass distribution of $\sim 750$ GeV, after analyzing new data collected at center-of-mass energies of $\sqrt{s} = 13$ TeV. We present a possible physical interpretation of such a signature, within the framework of a minimal UV-complete model with a massive singlet pseudoscalar state $a$ that couples to a new TeV-scale colored vectorlike fermion $F$, whose hypercharge quantum number is a non-zero integer. The pseudo-scalar state $a$ might be a heavy pseudo-Goldstone boson, such as a heavy axion, which decays into two photons and whose mass lies around the excess region. The mass of the CP-odd state $a$ and its coupling to $F$ may be due to nonperturbative effects, which can break the original Goldstone shift symmetry dynamically. The possible role that the heavy axion $a$ can play in the radiative generation of a seesaw Majorana scale and in the solution to the so-called strong CP problem is briefly discussed.

\[ \mathcal{L} = \bar{F}(iD - m_F)F + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}M_a^2a^2 - h_F a \bar{F}i\gamma_5 F. \]
the heavy axion and (4), it is straightforward to calculate the decay widths of shown in Fig. 1. The effective enhancement factor which includes the leading order fermion momenta are incoming, i.e., \( p + k + q = 0 \), the one-loop \( a(p) - A_\mu(k) - A_q(q) \) coupling reads [3–5]:

\[
\Gamma_{\mu\nu}(p,k,q) = i Q_F^2 N_C \alpha_{em} h_F \frac{m_F}{F_F} \left( \frac{p^2}{4m_F^2} \right) \epsilon_{\mu\nu\lambda\rho} k^\lambda q^\rho, \tag{2}
\]

where \( Q_F = Y_F/2 \) is the electric charge of the heavy fermion \( F \), \( N_C = 3 \) is its color degrees of freedom, \( \alpha_{em} = \frac{e^2}{4\pi} \) is the electromagnetic fine structure constant, and \( \epsilon_{\mu\nu\lambda\rho} \) is the usual antisymmetric Levi–Civita tensor (with the convention: \( \epsilon^{0123} = +1 \)). Moreover, the loop function \( F_F(\tau) \) was calculated a long time ago [3] and found to be

\[
F_F(\tau) = \begin{cases} 
\frac{1}{2} \arcsin^2 \sqrt{\tau}, & |\tau| \leq 1, \\
-\frac{1}{4\pi} \left[ \ln \left( \frac{\tau + \sqrt{\tau^2 - 1}}{\sqrt{\tau^2 - 1}} \right) - i\pi \right]^2; & |\tau| \geq 1.
\end{cases}
\tag{3}
\]

Note that for \( |\tau| \ll 1 \), we have \( F_F(\tau) = 1 + \tau/3 + O(\tau^2) \), whereas for \( |\tau| \gg 1 \), \( F_F(\tau) \to -\ln^2 |\tau|/(4\pi) \) which goes to zero asymptotically as \( \tau \to \infty \).

By analogy, the SU(3)_C global anomaly generates an effective interaction of the heavy axion \( a \) to gluons \( G_\mu \), as shown in Fig. 1. The effective \( a(p) - G_\mu(k) - G_\nu(q) \) coupling is given by

\[
\Gamma_{\mu\nu}(p,k,q) = i Q_F^2 N_C \alpha_{em} h_F \frac{m_F}{F_F} \left( \frac{p^2}{4m_F^2} \right) \epsilon_{\mu\nu\lambda\rho} k^\lambda q^\rho, \tag{4}
\]

where \( \alpha_s = g^2_s/(4\pi) \) is the strong fine structure constant.

With the aid of the effective couplings given in (2) and (4), it is straightforward to calculate the decay widths of the heavy axion \( a \) into photons (\( \gamma \)) and gluons (\( g \)):

\[
\Gamma(a \to \gamma \gamma) = \frac{N_C^2 \alpha_{em}^2 Q_F^4 h_F^2 M_a^3}{64\pi^3} |F_F(\tau_a)|^2, \tag{5}
\]

\[
\Gamma(a \to g g) = \frac{\alpha_s^2}{32\pi^2} h_F^2 M_a^3 |F_F(\tau_a)|^2 K_a^g, \tag{6}
\]

where \( \tau_a = M_a^2/(4m_F^2) \) and \( K_a^g \approx 1.6 \) is a QCD loop enhancement factor which includes the leading order QCD corrections [6]. In addition, the other diboson decay channels, such as \( a \to ZZ, Z\gamma \) and \( W^+W^- \), may be reliably estimated to leading order in \( M_Z^2/M_a^2 \) [7] as follows:

\[
\Gamma(a \to ZZ) \approx \frac{\sin^4 \theta_w}{\cos^4 \theta_w} \approx 0.082, \tag{7}
\]

\[
\Gamma(a \to g g) \approx \frac{2\sin^2 \theta_w}{\cos^2 \theta_w} \approx 0.57. \tag{8}
\]

whilst the decay width \( a \to W^+W^- \) is negligible, since the corresponding \( aW^+W^- \) effective coupling is generated at the two-loop level, e.g., from the one-loop induced \( \gamma \gamma \) coupling. To satisfy the LHC constraints on the masses of exotic colored fermions, we may assume that the vectorlike fermion \( F \) is heavier than \( a \), e.g., \( m_F \gtrsim 1.5 \) TeV, in which case \( \tau_a \ll 1 \). Hence, the loop function \( F_F(\tau_a) \) may well be approximated as \( F_F(\tau_a) \approx 1 \).

If we now take the ratio \( R \) of the photonic versus the gluonic decay width given in (5) and (6), we readily find that

\[
R = \frac{\Gamma(a \to \gamma \gamma)}{\Gamma(a \to g g)} = \frac{N_C^2 \alpha_{em}^2 Q_F^4}{2\alpha_s^2 K_a^g}. \tag{9}
\]

Observe that the ratio \( R \) is independent of the Yukawa coupling \( h_F \) and, for \( Q_F \gtrsim 2 \), we obtain \( R > 1 \) and the decay \( a \to \gamma \gamma \) can easily become the dominant mode.

The production cross section of heavy axions via gluon–gluon fusion [8] may be calculated as follows:

\[
\sigma(pp \to a \to \gamma \gamma) \approx \sigma(pp \to a) B(a \to \gamma \gamma), \tag{10}
\]

where \( B(a \to \gamma \gamma) \approx R/(1 + 1.57R) \) is the branching fraction for the decay channel \( a \to \gamma \gamma \), with \( R \) given in (8). For center-of-mass energies of \( \sqrt{s} = 13 \) TeV, we may naively estimate the cross section \( \sigma(pp \to a) \) as

\[
\sigma(pp \to a) \sim \sigma_{SM}(pp \to H) \times \frac{h_F^4 M_a^2}{m_H^4 M_a^4}, \tag{11}
\]

where \( \sigma_{SM}(pp \to H) \approx 40 \) pb is a reference production cross section of the SM Higgs boson \( H \) via gluon–gluon fusion, with \( M_H \approx 125 \) GeV [9]. Hence, for \( M_a = 750 \) GeV (or \( M_a/M_H = 6 \)), \( m_F/m_t = 10 \) and \( h_F = 0.1 \), we find that

\[
\sigma(pp \to a \to \gamma \gamma) \sim 15 \text{ fb} \times B(a \to \gamma \gamma). \tag{12}
\]
For \( B(a \to \gamma\gamma) \approx 1 \) and an integrated luminosity \( \mathcal{L} = 3 \text{ fb}^{-1} \) at \( \sqrt{s} = 13 \text{ TeV} \), we obtain about 45 signal events, which is compatible with the diphoton-excess events reported in [1].

As discussed in detail in [2], axionlike fields could act as mediators to generate TeV-scale gauge-invariant masses, such as \( m_\pi^2 F F \), for vectorlike fermions through global anomalies at the three-loop level. In particular, a gauge-invariant Majorana mass term \( m_M (\bar{e}_R \gamma^5 e_R)^C \) can be generated [10], if heavy axion fields couple to Kalb–Ramond axions [11,12] that occur in torsionful theories of quantum gravity. Light axions play an important role in solving the strong CP problem via the so-called Peccei–Quinn mechanism [13–16]. Thus, the possible presence of a heavy axion, or a multitude of axions [17,18], may give rise to interesting mixing phenomena and possibly to new effects in astrophysical considerations [19].

In conclusion, we have presented a minimal UV-complete model, based on the possible existence of a heavy axion with mass \( M_a \approx 750 \text{ GeV} \), which could offer a possible physical interpretation of the diphoton excess observed in the Run 2 data. The model requires the presence of a new TeV-scale colored vectorlike fermion \( F \), which has a nonzero integer hypercharge. For large electric charges \( Q_F \geq 2 \), the photonic decay mode \( a \to \gamma\gamma \) becomes naturally the dominant channel. The latter, along with the branching fractions given in (7), provide a unique prediction of our minimal model that can be tested with future Run 2 data. Nevertheless, our model may require an extension to its field content, as it exhibits a Landau pole at energy scales \( Q \lesssim 10^{14} \text{ GeV} \), for \( Q_F \geq 2 \). Further studies are therefore needed, so as to be able to fully assess the physical significance of the observed diphoton excess, as a firm signature of new physics at the LHC.

ACKNOWLEDGMENTS

The author thanks Andrew Pilkington for discussions on the ATLAS signal events. This work is supported in part by the Lancaster–Manchester–Sheffield Consortium for Fundamental Physics, under STFC Research Grant No. ST/L000520/1.


