QCD axion from aligned axions and Diphoton excess


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Overview on the recent diphoton excess at LHC Run 2
CTPU
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Diphoton excess around 750 GeV
  - Reported both by ATLAS and CMS with 2-3σ significance
  - Need more data to confirm

How to interpret the LHC diphoton excess
  - New physics beyond the SM?
  - A new resonance?
A possible (and simple) theoretical interpretation

- Axion decaying into two photons: $pp \rightarrow \text{axion} \rightarrow \gamma\gamma$
- Effective axion interactions

$$k_S \frac{g_3^2}{32\pi^2} \frac{a_{\text{hid}}}{f_{\text{hid}}} GG + k \frac{g_1^2}{32\pi^2} \frac{a_{\text{hid}}}{f_{\text{hid}}} BB$$

$G$ and $B$: $SU(3)_C$ and $U(1)_Y$ field strength

- Production via gluon-gluon fusion = constant $\times (k_S/f_{\text{hid}})^2$
- Branching ratio into photons = $0.001 \times (k/k_S)^2$
How to generate the axion couplings

- New vector-like heavy quarks (and/or leptons)
- Effective axion couplings to SM gauge bosons from heavy quark loops

The excess can be explained if

- \((\text{mass of hidden axion}) \sim 750 \text{ GeV}\)
- \((\text{decay constant of hidden axion}) \sim k \times 100 \text{ GeV}\)

\(\rightarrow (\text{heavy quark mass})\)

- Many papers: Harigaya, Nomura / Mambriri, Arcadi, Djouadi / Backovic, Mariotti, Redigolo / Angelescu, Djouadi, Moreau / Nakai, Sato, Tobioka / Knapen, Melia, Papucci, Zurek / Buttazzo, Greljo, Marzocca / Pilaftsis / Franceschini et al / Chiara, Marzola, Raida / Falkowski, Slone, Volansky / ...
Why such weak-scale axion exists in nature?

- Related with Strong CP Problem?
• Strong CP Problem

Why QCD almost preserves CP differently from EW interactions?

• Natural solution by QCD axion- NG boson of $U(1)_{PQ}$

\[
\frac{\Theta}{32\pi^2} G\tilde{G} \quad \text{where} \quad \Theta = \theta_{\text{bare}} + \arg(\det Y_{\text{quark}})
\]

\[
\frac{1}{32\pi^2} \frac{a_{\text{QCD}}}{f_{\text{QCD}}} G\tilde{G} \rightarrow \Theta = \left\langle \frac{a_{\text{QCD}}}{f_{\text{QCD}}} \right\rangle
\]

• Conventional axion window

\[10^9 \text{ GeV} < f_{\text{QCD}} < 10^{12} \text{ GeV}\]

• QCD axion: dark matter for $f_{\text{QCD}}$ in or above the window
Theoretical questions on QCD axion

- Which physics determines the QCD axion scale?
- How to protect $U(1)_{PQ}$ from quantum gravity effects?

Explicit PQ breaking in quantum gravity

- Additional axion potential

$$\Phi^{4+n} \frac{M^n}{M_{Pl}} + \text{h.c.} \rightarrow \Delta V = \left(\text{PQ breaking scale}\right)^{4+n} \cos \left( c_1 \frac{a_{QCD}}{f_{QCD}} + c_2 \right)$$

- For $f_{QCD} \sim \text{(PQ breaking scale)}$, $n \leq 10$ spoil the axion solution
- **QCD axion from aligned axions**
  - \( f_{\text{QCD}} \gg (\text{PQ breaking scale}) \) via Alignment Mechanism

- **Alignment Mechanism (multi axions)**
  - Hidden sector with \( N \) periodic axions: \( \phi_i \equiv \phi_i + 2\pi f_i \)
  - Decay constants \( f_i \sim f = \mathcal{O}(100) \) GeV – 1 TeV
  - Alignment by explicit breaking of \((N-1)\) shift symmetries
    → one axion with effective decay constant = \( e^{\mathcal{O}(1)} \times N \times f \gg f \)
    but without hierarchy among involved model parameters

Choi, Kim, Yun 2014
Choi, Im 2015
Kaplan, Rattazzi 2015
(see also Kim, Nilles, Peloso 2005)
- **QCD axion from aligned axions**
  - Identify the axion having an exponentially enhanced decay constant with the QCD axion
  \[ f_{\text{QCD}} = 10^{9-12} \text{ GeV} \] is obtained from \( N \geq 10 \) axions with \( f \sim 1\text{TeV} \)
  - Identify one of \((N-1)\) heavy axions with the hidden axion responsible for the diphoton excess
Model for QCD axion from aligned axions
Simple model

- N axions with

\[ \Delta L = -\sum_{i=1}^{N-1} \Lambda_i^4 \cos \left( \frac{\phi_i}{f_i} + n_i \frac{\phi_{i+1}}{f_{i+1}} \right) + k_S \frac{g_3^2}{32\pi^2} \frac{\phi_N}{f_N} G\tilde{G} + k \frac{g_1^2}{32\pi^2} \frac{\phi_N}{f_N} B\tilde{B} \]

alignment potential from loops of heavy PQ quarks (assumed to be SU(2)_L singlet)

- QCD axion composed of N axions

\[ f_{QCD} = \sqrt{\sum_{i=1}^{N} \sum_{j=1}^{N-1} n_j f_i^2} \approx e^{O(1) \times N} f \]

mass from the QCD instanton effects

From NP dynamics: Choi, Kim, Yun 2014, Choi, Im 2015
From clockwork potential: Kaplan, Rattazzi 2015

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- **Diphoton excess**
  
  - Identify one of \((N-1)\) heavy axions with \(a_{\text{hid}}\) around 750 GeV
    
    \[
    L_{\text{eff}} = k_S \frac{g_3^2}{32\pi^2} \frac{a_{\text{hid}}}{f_{\text{hid}}} G\tilde{G} + k \frac{g_1^2}{32\pi^2} \frac{a_{\text{hid}}}{f_{\text{hid}}} B\tilde{B} + m_{\text{hid}}^2 \left( \frac{a_{\text{hid}}}{f_{\text{hid}}} \right) \cos \left( \frac{a_{\text{hid}}}{f_{\text{hid}}} \right)
    \]
  
  - Decay into SM gauge bosons
    
    \[
    \Gamma_{a_{\text{hid}} \rightarrow \gamma\gamma} : \Gamma_{a_{\text{hid}} \rightarrow Z\gamma} : \Gamma_{a_{\text{hid}} \rightarrow ZZ} : \Gamma_{a_{\text{hid}} \rightarrow WW} = 1 : 2 \tan^2 \theta_W : \tan^4 \theta_W : 0 = 1 : 0.6 : 0.08 : 0
    \]
    
    \(\rightarrow\) mild tension with constraint on \(Z\gamma\) mode at 8TeV run
    
    \[
    \Gamma_{a_{\text{hid}} \rightarrow gg} = 0.4\text{GeV} \left( \frac{f_{\text{hid}} / k_S}{100\text{GeV}} \right)^2 \quad \text{and} \quad \text{Br}(a_{\text{hid}} \rightarrow \gamma\gamma) \approx \frac{\Gamma_{a_{\text{hid}} \rightarrow \gamma\gamma}}{\Gamma_{a_{\text{hid}} \rightarrow gg}} = 0.001 \left( \frac{k}{k_S} \right)^2
    \]
    
    \(\rightarrow\) narrow width resonance
  
  - **Reported diphoton excess: explained for** \(f_{\text{hid}} \sim k \times 100\) GeV
• **Interesting and distinctive features**
  - **Broad width (not significant yet) due to multiple peaks?**
    - Some of heavy axions may have masses close to each other
    - In UV completion, saxion for each axion
      - Coupling to GG and BB, a saxion can also explain the excess
    - Invisible decay of axion/saxion into hidden sector
  - **Multiple axions and saxions**
    - Many signals around or above TeV
Possible UV completion
Clockwork axion

- $N$ complex scalar with

$$L = -\sum_{i=1}^{N} (\frac{m^{2}}{2} |\Phi_{i}|^{2} + \lambda |\Phi_{i}|^{4}) + \sum_{i=1}^{N-1} (\varepsilon \Phi_{i}^{*}\Phi_{i+1}^{3} + \text{h.c.}) + y_{q} \Phi_{N} \sum_{\alpha=1}^{n_{q}} \bar{Q}_{\alpha} Q_{\alpha} + y_{\ell} \Phi_{N} \sum_{\alpha=1}^{n_{l}} \bar{L}_{\alpha} L_{\alpha}$$

- Coupling to gluons: $k_{S} = n_{q}$
- Coupling to photons: $k = 3a^{2}n_{q} + b^{2}n_{l}$

(a, b: hypercharge of $Q$ and $L$)
- $f_{hid} \sim k \times 100 \text{ GeV}$ is around or above TeV for $k \sim 10$
- High quality of PQ symmetry
  - \textbf{Z}_2 \text{ parity} (remnant of some gauge symmetry): \( \Phi_i \rightarrow -\Phi_i \)
    - Forbids odd power potential terms
  - Most dangerous PQ breaking term
    \[
    \frac{\lambda}{6! M_{Pl}^2} \Phi_1^6 + \text{h.c.} \rightarrow \text{shift of the minimum of QCD axion potential}
    \]
    \[
    \Delta m_{a_{\text{QCD}}} = 4 \times 10^{-5} \text{eV} \sqrt{\text{Re} \lambda} \left( \frac{f_1}{1 \text{TeV}} \right)^2
    \]
    \[
    \bar{\theta} = 10^{-10} \left( \text{Im} \lambda \right) \left( \frac{f_1}{1 \text{TeV}} \right)^5 \left( \frac{f_{\text{QCD}}}{10^{10} \text{GeV}} \right)
    \]
  - Testable CP violation!
  - Small (but not negligible) extra axion mass
Discussion (work in progress)

- Why $f$ is around TeV?
  - Due to saxion cosmology?
  - Connection to supersymmetry breaking scale?
- Effect of explicit PQ breaking in quantum gravity?
  - Testable CP violation in QCD
  - Different cosmology from the conventional axion model
  - Supersymmetric set-up:
    holomorphicity and $Z_3$ can explain high quality of $U(1)_{\text{PQ}}$
Summary
• The reported diphoton excess may be the signal of BSM physics

• Model with QCD axion from aligned axions
  • Can explain the excess while solving Strong CP Problem and Dark Matter Problem
  • Can lead to non-trivial peak structure
  • May answer the theoretical questions on QCD axion

• Need more data to confirm the excess and validate the model

Thank you!