QCD axion from aligned axions and Diphoton excess

T. Higaki, KSJ, N. Kitajima, F. Takahashi, arXiv: 1512.05295 and 1601.xxxxx

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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→ axion →γγ
  - Effective axion interactions

$$k_S \frac{g_3^2}{32\pi^2} \frac{a_{\text{hid}}}{f_{\text{hid}}} G\tilde{G} + k \frac{g_1^2}{32\pi^2} \frac{a_{\text{hid}}}{f_{\text{hid}}} B\tilde{B}$$

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

  - Production via gluon-gluon fusion = constant×$(k_S/f_{hid})^2$
  - Branching ratio into photons = 0.001×$(k/k_S)^2$

- 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
  - (mass of hidden axion) ~ 750 GeV
  - (decay constant of hidden axion) ~ k×100 GeV

    → (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 $U(1)_{PQ}$

Peccei and Quinn 1977

$$\frac{\bar{\theta}}{32\pi^2} G\tilde{G} \quad \text{where} \quad \bar{\theta} = \theta_{\text{bare}} + \arg(\det Y_{\text{quark}})$$

$$\frac{1}{32\pi^2}\frac{a_{\text{QCD}}}{f_{\text{QCD}}} G\tilde{G} \quad \rightarrow \quad \bar{\theta} = \left\langle \frac{a_{\text{QCD}}}{f_{\text{QCD}}} \right\rangle$$

- Conventional axion window

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

- QCD axion: dark matter for f_{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

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

  - For f_{QCD}~(PQ breaking scale), $n \leq 10$ spoil the axion solution

- QCD axion from aligned axions
  - $f_{QCD} \gg$ (PQ breaking scale) via Alignment Mechanism

- Alignment Mechanism (multi axions)

Choi, Kim, Yun 2014
Choi, Im 2015
Kaplan, Rattazzi 2015
(see also Kim, Nilles, Peloso 2005)

  - Hidden sector with N periodic axions: $\phi_i \equiv \phi_i + 2\pi f_i$
  - Decay constants f_i ~ f= O(100) GeV – 1 TeV
  - Alignment by explicit breaking of (N-1) shift symmetries

    → one axion with effective decay constant = $e^{O(1)\times N} \times f \gg f$

    but without hierarchy among involved model parameters

Choi, Kim, Yun 2014

- QCD axion from aligned axions
  - Identify the axion having an exponentially enhanced decay constant with the QCD axion

  → $f_{QCD}=10^{9\text{-}12}$ GeV is obtained from N≥10 axions with f ~ 1TeV
  - 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

From NP dynamics: Choi, Kim, Yun 2014, Choi, Im 2015

From clockwork potential: Kaplan, Rattazzi 2015

  - 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

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

mass from the QCD instanton effects

- Diphoton excess
  - Identify one of (N-1) heavy axions with a_{hid} around 750 GeV

$$L_{\text{eff}} = k_S \frac{g_3^2}{32\pi^2} \frac{a_{\text{hid}}}{f_{\text{hid}}} G\tilde{G} + k \frac{g_1^2}{32\pi^2} \frac{a_{\text{hid}}}{f_{\text{hid}}} B\tilde{B} + m_{\text{hid}}^2 f_{\text{hid}}^2 \cos\left(\frac{a_{\text{hid}}}{f_{\text{hid}}}\right)$$

  - Decay into SM gauge bosons

$$\Gamma_{a_{\text{hid}}\to\gamma\gamma} : \Gamma_{a_{\text{hid}}\to Z\gamma} : \Gamma_{a_{\text{hid}}\to ZZ} : \Gamma_{a_{\text{hid}}\to WW} = 1 : 2\tan^2\theta_W : \tan^4\theta_W : 0 = 1 : 0.6 : 0.08 : 0$$

→ mild tension with constraint on Zγ mode at 8TeV run

$$\Gamma_{a_{\text{hid}}\to gg} = 0.4\text{GeV}\left(\frac{f_{\text{hid}}/k_S}{100\text{GeV}}\right)^{-2} \quad \text{and} \quad \text{Br}(a_{\text{hid}} \to \gamma\gamma) \simeq \frac{\Gamma_{a_{\text{hid}}\to\gamma\gamma}}{\Gamma_{a_{\text{hid}}\to gg}} = 0.001\left(\frac{k}{k_S}\right)^2$$

→ narrow width resonance

  - Reported diphoton excess: explained for f_{hid}~k×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

Kaplan and Rattazzi 2015

- Clockwork axion
  - N complex scalar with

$$L = -\underbrace{\sum_{i=1}^{N}\left(-m^2\left|\Phi_i\right|^2 + \lambda\left|\Phi_i\right|^4\right)}_{\text{stabilization}} + \underbrace{\sum_{i=1}^{N-1}\left(\varepsilon\Phi_i^*\Phi_{i+1}^3 + \text{h.c.}\right)}_{\text{alignment}} + \underbrace{y_q\Phi_N\sum_{\alpha=1}^{n_q}\bar{Q}_\alpha Q_\alpha + + y_\ell\Phi_N\sum_{\alpha=1}^{n_\ell}\bar{L}_\alpha L_\alpha}_{\text{effective axion couplings}}$$

  - 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)
  - $f_{hid} \sim k \times 100$ GeV is around or above TeV for $k \sim 10$

- High quality of PQ symmetry
  - Z_2 parity (remnant of some gauge symmetry): $\Phi_i \to -\Phi_i$

    - Forbids odd power potential terms
  - Most dangerous PQ breaking term

$$\frac{\lambda}{6!}\frac{\Phi_1^6}{M_{Pl}^2} + \text{h.c.} \;\to\; \text{shift of the minimum of QCD axion potential}$$

$$\Delta m_{a_{\text{QCD}}} = 4\times 10^{-5}\,\text{eV}\sqrt{\text{Re}\,\lambda}\left(\frac{f_1}{1\text{TeV}}\right)^2$$

$$\bar{\theta} = 10^{-10}\left(\text{Im}\,\lambda\right)\left(\frac{f_1}{1\text{TeV}}\right)^5\left(\frac{f_{\text{QCD}}}{10^{10}\,\text{GeV}}\right)$$

- Testable CP violation!

- Small (but not negligible) extra axion mass

Higaki, KSJ, Kitajima, Takahashi

- 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 $U(1)_{PQ}$

❖ 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!