A Model of Heavy QCD Axion and the LHC Signature

arXiv:1504.06084, 1602.07909, 1607.01936

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Outline

1. Heavy axion - Why and How?
2. Our model and the LHC signature
Strong CP Problem

- QCD should break CP symmetry
  \[ \theta = \theta_{YM} + \arg \det(Y_u Y_d) \]
- The PQ mechanism can set \( \theta = 0 \).
  - The original model has been excluded.
What is the Alternative?

- Roughly, two choices:
  - Larger $f_a$ / Heavier $m_a$

Axion Mass

$$m_a^2 \approx \frac{m_q \Lambda^3}{f_a^2}$$

indicates heavier $m_a$ is difficult.
Higher Dimensional Operator

\[ \Delta \mathcal{L} = c \frac{\phi^5}{M_{Pl}} \]

\[ \Rightarrow \Delta \theta \approx c \frac{f_a^3}{M_{Pl} m_a^2} \gg 10^{-10}, \]

indicates heavier \( m_a \) is preferred!
Realizing a Heavy Axion

- (Rubakov, 1997) suggested a consistent way to achieve a heavy axion

Rubakov 1997; Berezhiani, Gianfagna and Giannotti 2000
Hook 2014, HF, Harigaya, Ibe and Yanagida 2015, Albaid, Dine and Draper 2015
(Kobakhidze 2016), (Gherghetta, Nagata and Shifman 2016)
How to Make an Axion Heavier?

- Another gauge theory is needed.
Another gauge theory is needed

Then how can we align the two $\theta$s?
\[ \theta = \theta_{YM} + \arg \det(Y_u Y_d) \]

- \( \theta' \) must also have Yukawa sector
- Thus, we need a complete copy of SM
  - We assume \( \mathbb{Z}_2 \) parity, which is spontaneously broken
Our Model

\[ u_R, d_R, Q_L, e_R, L_L \]
\[ H, N_R \]
\[ \psi \]

\[ u'_R, d'_R, Q'_L, e'_R, L'_L \]
\[ H', N'_R \]
\[ \psi' \]

\[ \mathbb{Z}_2 \]

PQ symmetry

HF, Harigaya, Ibe and Yanagida, arXiv:1504.06084
Axion $\alpha$

$$m_{\alpha} \gtrsim 400 \text{ MeV}$$

Vector like quark $\psi, \psi'$

$$m_{\psi} = \frac{1}{\sqrt{2}} g f_{\alpha} \gtrsim 900 \text{ GeV}$$

Dilaton $s$

$$m_s = \sqrt{2\lambda} f_{\alpha} \gtrsim \mathcal{O}(100) \text{ GeV}$$
Axion $a$

\[ m_a \geq 400 \text{ MeV} \]

Vector like quark $\psi, \psi'$

\[ m_\psi = \frac{1}{\sqrt{2}} g f_a \geq 900 \text{ GeV} \]

Dilaton $s$

\[ m_s = \sqrt{2}\lambda f_a \approx 750 \text{ GeV}?? \]

or, "let us consider the LHC signal of the dilaton"...
Effective Lagrangian

\[ \mathcal{L} = \frac{s}{f_a} \partial a \partial a + N_1 \frac{\alpha_s}{8\pi} \frac{s}{f_a} GG + N_2 \frac{\alpha}{8\pi} \frac{s}{f_a} F^{(\prime)} F^{(\prime)} \]

\[ + N_1 \frac{\alpha_s}{8\pi} \frac{a}{f_a} G\tilde{G} + N_2 \frac{\alpha}{8\pi} \frac{a}{f_a} F^{(\prime)} \tilde{F}^{(\prime)} \]

- \( s\partial a \partial a \) is the strongest
- How does it look?
Photons and Photon Jets

- ECAL can’t count the number of $\gamma$
- The decay looks like “diphoton”!
Difference b/w $\gamma$s and $\gamma$-jets

- Some $\gamma$s are “converted”
How to Distinguish the Jet

- We simulate trackers in CMS.
  - Conversion, bremsstrahlung, . . .
- $p_T^{\text{track}}$ has greater discrimination power!

HF, Ibe, Jinnouchi and Nojiri, arXiv:1607.01936

$X$, $Y(\tau = 0)$, $Z(\tau = 0)$, SM BG

(X: $\gamma$, Y: $2\gamma$, Z: $4\gamma$)
Axion Decay

Lagrangian

\[ \mathcal{L}_a = N_1 \frac{\alpha_s}{8\pi} \frac{a}{f_a} G^{(i)} \tilde{G}^{(i)} + N_2 \frac{\alpha}{8\pi} \frac{a}{f_a} F^{(i)} \tilde{F}^{(i)} \]

- We need large BR
  - \( \text{BR}(s \to 4\gamma) = \text{BR}(a \to 2\gamma)^2 \)
- \( a-G-G \) coupling looks too strong
Mixings with Mesons

- The phase space suppresses $a \to 3\pi$

Chiang, HF, Ibe and Yanagida, arXiv:1602.07909
Summary

- The heavy axion is plausible
- The dilaton may appear at the LHC as a “di-photon-jet” signal.
- “Diphoton” and “Di-photon-jet” is distinguishable using $p_T$