Possibility of the Heavy QCD Axion

arXiv:1504.06084, 1602.07909, xxxx.xxxxx

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Strong CP Problem

- QCD should break CP symmetry

$$\theta = \theta_{\mathsf{YM}} + \arg\det(Y_u Y_d)$$

- 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

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

indicates heavier m_a is difficult.

Higher Dimensional Operator?

- Why not?

$$\Delta\mathcal{L} = c\frac{\phi^5}{M_{\mathsf{Pl}}}$$

$$\Rightarrow \Delta\theta \simeq c\frac{{f_a}^3}{M_{\mathsf{Pl}}{m_a}^2} \gg 10^{-10},$$

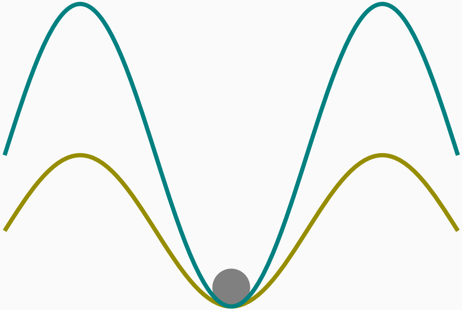
Realizing a Heavy Axion

- (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
(Gherghetta, Nagata and Shifman 2016)

How to Make an Axion Heavier?

- Another gauge theory is needed



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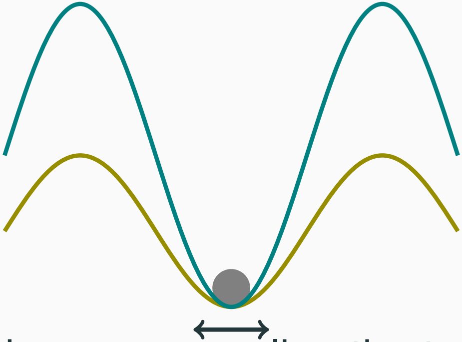


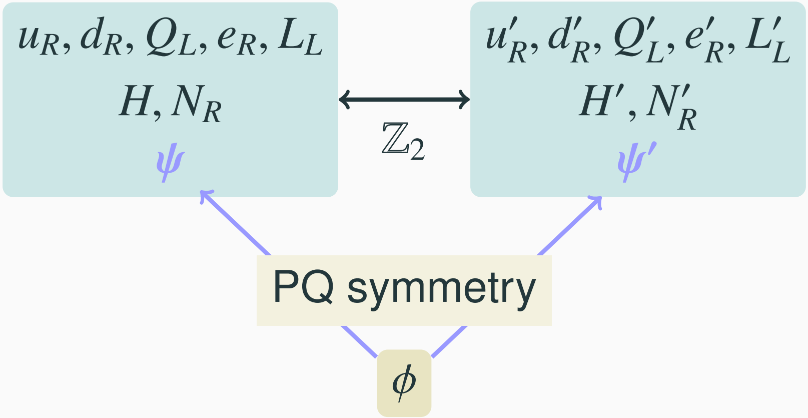
Then how can we align the two θs?

Copy of SM

$$\theta = \theta_{\mathsf{YM}} + \boxed{\arg\det(Y_u Y_d)}$$

- θ' 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
ψ
$\mathbb{Z}_2$
$u'_R, d'_R, Q'_L, e'_R, L'_L$
H', N'_R
ψ'
PQ symmetry
ϕ

Low Energy Spectrum

Axion a

$$m_a \gtrsim 400\,\text{MeV}$$

Vector like quark ψ, ψ'

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

Dilaton s

$$m_s = \sqrt{2\lambda} f_a \gtrsim \mathcal{O}(100)\,\text{GeV}$$

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Dilaton s

$$m_s = \sqrt{2\lambda} f_a \boxed{\simeq 750\,\text{GeV??}}$$

or yet another diphoton...

Dilaton Decay

- Obviously, $\frac{s}{f_a}\partial a \partial a$ is the strongest
- Almost no $s \to 2\gamma^{(\prime)}$ decay
- Does it fail?

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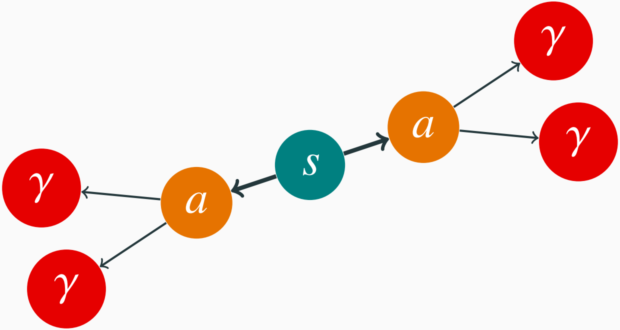
- Obviously, $\frac{s}{f_a}\partial a \partial a$ is the strongest
- Almost no $s \to 2\gamma^{(\prime)}$ decay
- Does it fail? - **No!**

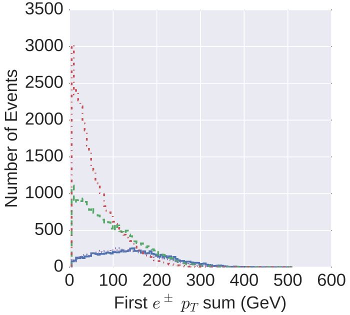
Photons and Photon Jets

- ECAL can't count the number of γ
  - Use "$s \to 2a$, $a \to 2$ collinear γ" mode



How to Distinguish the Jet

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



(X:γ, Y:2γ, Z:4γ)

HF, Ibe, Jinnouchi and Nojiri,
arXiv:xxxx.xxxxx

Axion Decay

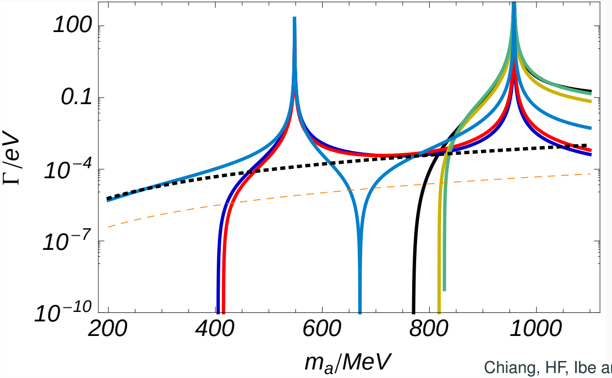
Lagrangian

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

- We need large BR
    - BR$(s \to 4\gamma)$ = 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 diphoton excess may be explained as the dilaton in our model
- “Diphoton” and “Di-photon-jet” is distinguishable using p_T