Color Unified Dynamical Axion

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Based on arXiv:1805.06465

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Strong CP problem

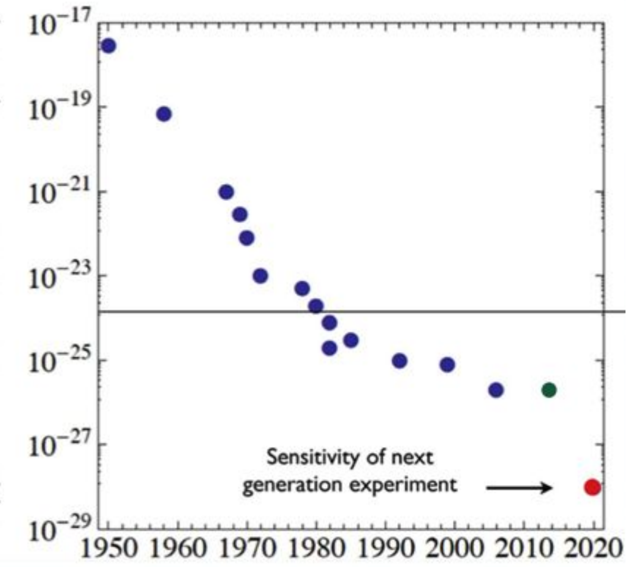
$$\mathcal{L}_{QCD} \supset \mathcal{L}_{\not{CP}} = -\bar{q} m e^{i\beta} q + \theta_{QCD} \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

One physical CPV phase: $\bar{\theta} = \theta_{QCD} + \arg\det M$

$$d_n \approx 10^{-16} |\bar{\theta}| \mathrm{e} \cdot \mathrm{cm} \qquad \bar{\theta} \lesssim 10^{-10}$$

Why is it so small?

Neutron EDM (Electric Dipole Moment)



[B.Fillipone via diLuzio]

Strong CP problem: massless quark solution

- Under a chiral rotation: $U(1)_A: \quad q \to e^{\frac{\alpha}{2} i\gamma_5} q$

$$\mathcal{L} \supset -m_q \bar{q} q - \theta \frac{\alpha_s}{8\pi} G\tilde{G} \longrightarrow -m_q \bar{q} e^{i\alpha\gamma_5} q - (\theta - \alpha) \frac{\alpha_s}{8\pi} G\tilde{G}$$

- If $m_q = 0$, the phase θ can be fully reabsorbed $\Longrightarrow$ **Strong CP Problem solved!**

- No different from usual PQ solution: [Peccei+Quinn 77]
  - $U(1)_{PQ}$ classically conserved
  - Explicitly broken by the QCD anomaly
  - Spontaneously broken at f_a (by $\langle \bar{q} q \rangle$)

- Most economical option: Massless up quark, disfavored by lattice data [Manohar et al 16, PDG]

Dynamical Axion

[Choi+Kim 85]

- ➔ Exotic massless quark ψ **How do we hide it?**
- ➔ New confining group $\tilde{\Lambda} \gg \Lambda_{QCD}$
  - ◆ $SU(\tilde{N})$ confines, bound states $m \sim \tilde{\Lambda}$
  - ◆ **Problem:** new CP violating phase $\tilde{\theta}$
- ➔ Add another massless quark χ
- ➔ $SU(\tilde{N})$ Confines + Chiral Symmetry Breaking:

Massless quark content

	$SU(3)_c$	$SU(\tilde{N})$
ψ	$\square$	$\square$
χ	1	$\square$

$$U(4)_L \times U(4)_R \xrightarrow[\langle\bar{\psi}\psi\rangle]{\langle\bar{\chi}\chi\rangle} U(4)_V$$

pseudo-Goldstone Bosons (pGB): $16 = 8 + 3 + \bar{3} + 1 + 1$

$$4\pi f_a \sim \tilde{\Lambda}$$

The η' become dynamical axions

My definition of axion:

"Any Goldstone Boson of a global U(1) symmetry, exactly conserved at the classical level but explicitly broken by instantons"

Dynamical Axion: masses

[Choi+Kim 85]

➔ Two axions: $\bar{\psi}\psi \quad \bar{\chi}\chi$

$$2\,\not{PQ}\ \text{instantons}\begin{cases}\Lambda_{QCD}\\ \tilde{\Lambda}\end{cases} \quad \textit{VS} \quad 3\ \text{pseudoscalars}\begin{cases}\bar{\psi}\psi\\ \bar{\chi}\chi\\ \eta'_{QCD}\end{cases}$$

➔ **One axion remains light:**

$$m_{a_1}^2 f_a^2 \sim \tilde{\Lambda}^4 \qquad m_{\eta'}^2 f_\pi^2 \sim \Lambda_{QCD}^4 \qquad m_{a_2}^2 f_a^2 \sim m_\pi^2 f_\pi^2 \frac{m_u m_d}{(m_u + m_d)^2}$$

UV completion of a usual invisible axion

Alternatives to the dynamical Axion

➔ Only one massless quark and a Z_2 [Hook 15]

➔ Complete copy of the SM

➔ The Z_2 ensures $\theta_2 = \theta_{QCD}$

➔ No light axion: $m^2 \sim \frac{\Lambda_2^4}{f_a^2}$

➔ The mirror EW sector has a large vev:

$$v_2 \gg v \implies m'_q \gg m_q, \implies \Lambda' \gg \Lambda_{QCD}$$

Z_2

	$SU(3)_c$	$SU(3)_2$
ψ	$\square$	$\square$
~~χ~~	~~1~~	~~$\square$~~

In our work: UNIFICATION

Color Unified Dynamical Axion: First try

➔ Unification allows to identify the two phases: only one massless quark needed

$$SU(6) \xrightarrow{\Lambda_{\rm CUT}} SU(3)_c \times SU(\tilde{3}) \times U(1)$$

➔ SM quarks are embedded in fundamentals of SU(6)

$$Q_L \equiv (q\,,\,\tilde{q})_L\,,\;\; U \equiv (u\,,\,\tilde{u})_R\,,\;\; D \equiv (d\,,\,\tilde{d})_R$$

Problem: Need to decouple the SM quark partners

1. Without spoiling SM quark masses
2. Without breaking EW at a high scale
3. In order to separate the running of the two groups .

We need an extra prime sector

Over Unification scale:

	$SU(6)$	$SU(2)_L$	$U(1)$
Ψ_L	20	1	0

Bellow unification scale:

	$SU(3)_c$	$SU(\tilde{3})$
ψ_L	$\square$	$\bar{\square}$
ψ_L^c	$\bar{\square}$	$\square$
$2\times\psi_\nu$	1	1

Color Unified Dynamical Axion: The real thing

$$SU(6) \times SU(3') \xrightarrow{\Lambda_{\rm CUT}} SU(3)_c \times SU(3)_{\rm diag}$$

➔ Spontaneously broken by the vev of Δ

$$\langle \Delta \rangle = \Lambda_{\rm CUT} \begin{pmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Allows for a large mass for the tilde sector without spoiling the SM quark masses

$$\kappa_q \, q'_L \Delta^* Q_L \longrightarrow \Lambda_{\rm CUT} \, \kappa_q \, q'_L \tilde{q}_L$$

	$SU(6)$	$SU(3')$
Q_L	$\square$	1
U^c_L	$\bar{\square}$	1
D^c_L	$\bar{\square}$	1
Ψ_L	20	1
q'_L	1	$\bar{\square}$
u'^c_L	1	$\square$
d'^c_L	1	$\square$
Δ	$\square$	$\bar{\square}$

	$SU(3)_c$	$SU(3)_{\rm diag}$	$SU(2)_L$	$U(1)_Y$
q_L	$\square$	1	$\square$	$\frac{1}{6}$
$\tilde{\rm q}_{\rm L}$	1	$\square$	$\square$	$\frac{1}{6}$
u^c_L	$\bar{\square}$	1	1	$-\frac{2}{3}$
$\tilde{\rm u}^{\rm c}_{\rm L}$	1	$\bar{\square}$	1	$-\frac{2}{3}$
d^c_L	$\bar{\square}$	1	1	$\frac{1}{3}$
$\tilde{\rm d}^{\rm c}_{\rm L}$	1	$\bar{\square}$	1	$\frac{1}{3}$
ψ_L	$\square$	$\bar{\square}$	1	0
ψ^c_L	$\bar{\square}$	$\square$	1	0
$2 \times \psi_\nu$	1	1	1	1
${\rm q}'_{\rm L}$	1	$\bar{\square}$	$\square$	$-\frac{1}{6}$
${\rm u}'^{\rm c}_{\rm L}$	1	$\square$	1	$\frac{2}{3}$
${\rm d}'^{\rm c}_{\rm L}$	1	$\square$	1	$-\frac{1}{3}$
–	–	–	1	0

Color Unified Dynamical Axion

$$\mathcal{L} \ni \Lambda_{\rm CUT} \left\{ \kappa_q \, q'_L \tilde{q}_L + \kappa_u \, u'^c_L \tilde{u}^c_L + \kappa_d \, d'^c_L \tilde{d}^c_L \right\} + \text{h.c.}$$

➔ Succesfully decoupled tilde and prime quarks $m \sim \Lambda_{CUT}$

➔ **Problem:** with an extra gauge group $\Longrightarrow$ extra CP phase, two options:

- **Model I:** Add an extra massless quark χ

	$SU(6)$	$SU(3)'$
ψ	$\square$	$\square$
χ	1	$\square$

We will focus on

- Model II: Add an extra scalar Δ_1, Δ_2

  Hybrid solution with a dynamical axion and a fundamental one.

Running of the gauge couplings

➔ At the breaking scale:

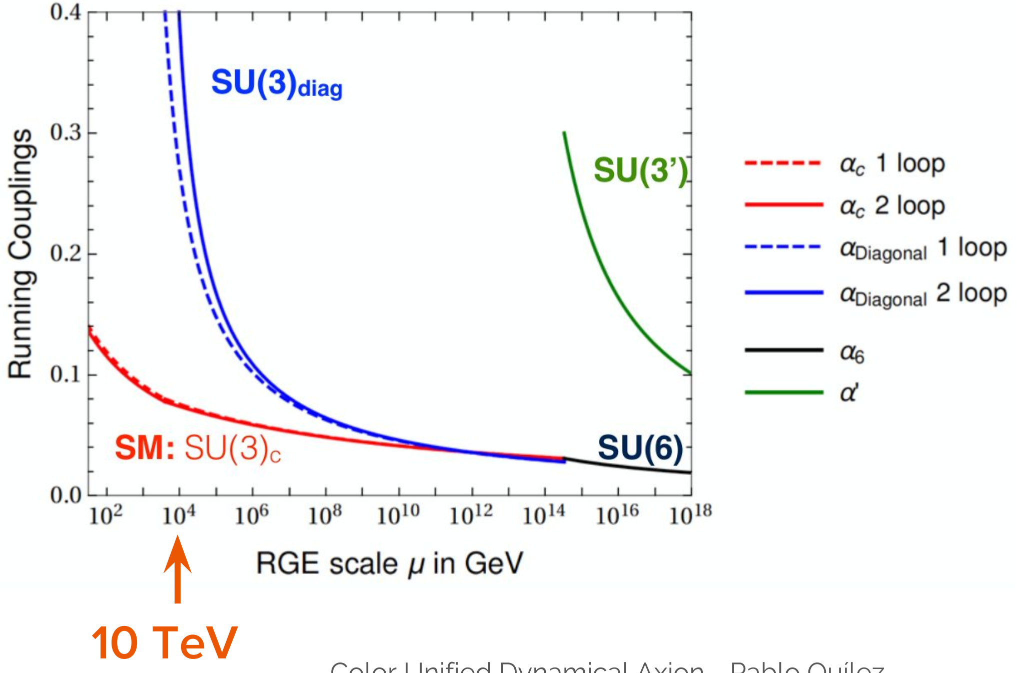
$$SU(6) \times SU(3') \xrightarrow{\Lambda_{\rm CUT}} SU(3)_c \times SU(3)_{\rm diag}$$

$$\frac{1}{\alpha_{\rm diag}(\mu)} = \frac{1}{\alpha_6(\mu)} + \frac{1}{\alpha'(\mu)}$$

$$\alpha_c(\Lambda_{\rm CUT}) = \alpha_6(\Lambda_{\rm CUT})$$

$SU(3)_{\rm diag}$ confines before QCD

$$\Lambda_{\rm d} \gg \Lambda_{QCD}$$



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Confinement and χSB of the $SU(3)_{diag}$

➔ Chiral symmetry breaking by the condensates: $\langle\bar{\psi}\psi\rangle, \ \langle\bar{\chi}\chi\rangle$

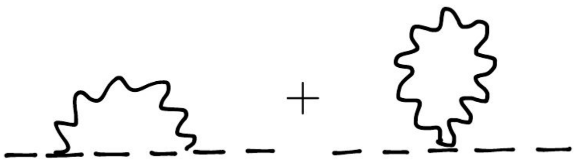
	$SU(3)_c$	$SU(3)_{\text{diag}}$
ψ	$\square$	$\square$
χ	1	$\square$

$$U(4)_L \times U(4)_R \xrightarrow{\Lambda_d} U(4)_V$$

➔ Results in 16 pGB's: $16 = 8_c + 3_c + \bar{3}_c + 1_c + 1_c$

become dynamical axions

➔ The "axipions", through quadratically divergent gluon loops, get a large mass:



$$\Rightarrow$$

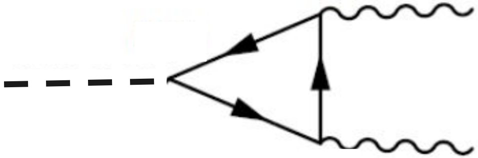
$$m^2(8_c) \approx \frac{9\alpha_c}{4\pi}\Lambda^2_{\text{diag}} \qquad \bar{\psi}t^a\psi,$$

$$m^2(3_c) \approx \frac{\alpha_c}{\pi}\Lambda^2_{\text{diag}} \qquad \bar{\psi}\chi, \ \bar{\chi}\psi$$

The η' pseudoscalars

➔ Anomalous currents $\Longrightarrow$ Anomalous couplings of the pseudoscalars:

$$j^{\mu}_{\psi_A} = \bar{\psi}\gamma^{\mu}\gamma^{5}\psi \equiv f_{\rm d}\,\partial^{\mu}\eta'_{\psi}\,,$$
$$j^{\mu}_{\chi_A} = \bar{\chi}\gamma^{\mu}\gamma^{5}\chi \equiv f_{\rm d}\,\partial^{\mu}\eta'_{\chi}\,,$$



$$\mathcal{L} \supset -\frac{\alpha_6}{8\pi}\frac{\sqrt{6}\,\eta'_{\psi}}{f_{\rm d}}G_6\tilde{G}_6 - \frac{\alpha'}{8\pi}\frac{2\,\eta'_{\chi}}{f_{\rm d}}G'\tilde{G}'$$

Λ_{CUT}

$$\mathcal{L} \supset -\frac{\alpha_c}{8\pi}\frac{\sqrt{6}\,\eta'_{\psi}}{f_{\rm d}}G_c\tilde{G}_c - \frac{\alpha_{\rm diag}}{8\pi}\left(2\,\frac{\eta'_{\chi}}{f_{\rm d}} + \sqrt{6}\,\frac{\eta'_{\psi}}{f_{\rm d}}\right)G_{\rm diag}\tilde{G}_{\rm diag}$$

Confinement

$$\mathcal{L} \supset \Lambda^4_{\rm diag}\,\cos\left(2\,\frac{\eta'_{\chi}}{f_{\rm d}} + \sqrt{6}\,\frac{\eta'_{\psi}}{f_{\rm d}}\right) + \Lambda^4_{\rm QCD}\,\cos\left(2\,\frac{\eta'_{\rm QCD}}{f_{\pi}} + \sqrt{6}\,\frac{\eta'_{\psi}}{f_{\rm d}}\right)$$

Incorporating η'_{QCD}

➔ 3 anomalous pseudoscalars
➔ 2 sources of mass/breaking

Another light axion model?

arXiv:1805.06465

Small Size Instantons and axion mass

- ➔ Typically, at high energies (= small size) couplings are very small.
- ➔ The instanton density has an exponential suppression:

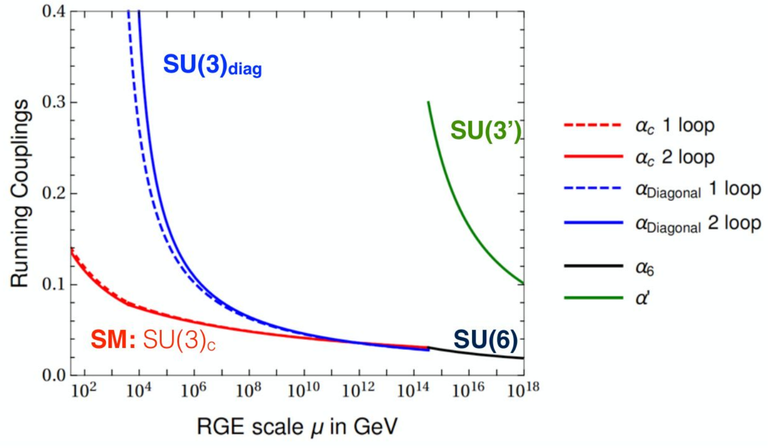
$$D[\alpha'(\mu)] \propto e^{-2\pi/\alpha'(\mu)}$$

Usually sizable only at the confinement scale

$$\left(e^{-2\pi/0.1} \sim 10^{-28}\right)$$

- ➔ New Physics can change the RG flow and induce a new source of axion mass

[Holdom+Peskin, 82]
[Dine+Seiberg, 86]
[Flynn+Randall, 87]
[Agrawal+Howe, 17]



- ➔ Large coupling $\alpha' \sim 0.3$
- ➔ Large breaking scale

$$\Lambda_{CUT} \sim 10^{14-18}\, GeV$$

New sizable contribution to the axion mass!!

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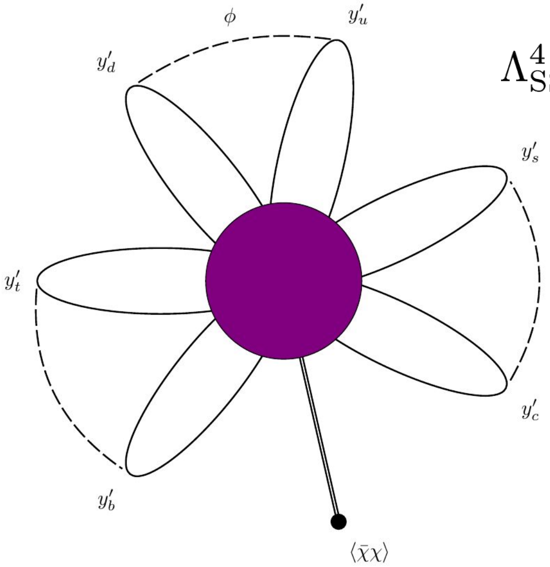
Small Size Instantons and axion mass

[t'Hooft, 73]
[Callan+Dashen+Gross, 77]
[Shifman+Vainshtein+Zakharov, 80]

➔ Dilute Instanton Gas approximation:



$$\Lambda^4_{\rm SSI} = -C_{inst}\int\frac{d\rho}{\rho^5}\left(\frac{2\pi}{\alpha'(\rho)}\right)^{2N_c} e^{-2\pi/\alpha'(\rho)}\left(\frac{2}{3}\pi^2\rho^3\,\langle\bar{\chi}\chi\rangle\right)\frac{1}{(4\pi)^6}\prod_i y'^{\,i}_u y'^{\,i}_d$$

Pure Yang-Mills Instanton — Fermionic suppression

$$\mathcal{L}_{eff} = \Lambda^4_{\rm SSI}\,\cos\left(2\,\frac{\eta'_\chi}{f_{\rm d}}\right)$$

$$\Lambda_{SSI} \gtrsim 20\,TeV$$

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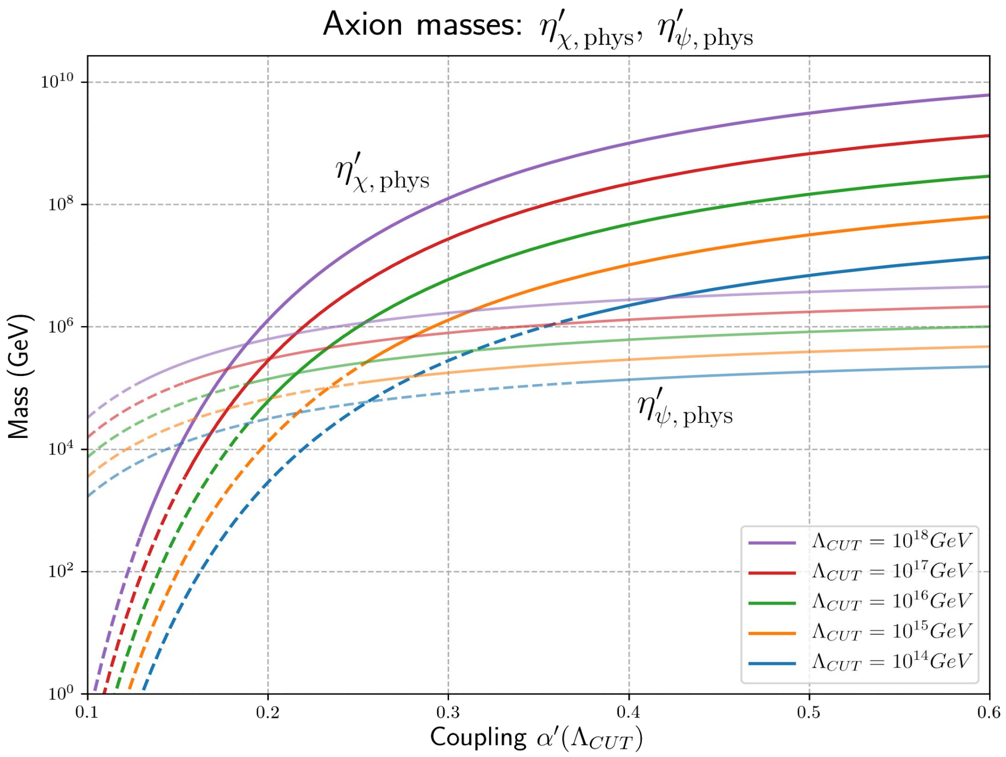
Dynamical axion potential and masses

$$\mathcal{L}_{eff} = \underbrace{\Lambda^4_{\rm SSI}\,\cos\left(2\,\frac{\eta'_\chi}{f_{\rm d}}\right)}_{SU(3')\ \text{SSI Instantons}} + \underbrace{\Lambda^4_{\rm diag}\,\cos\left(2\,\frac{\eta'_\chi}{f_{\rm d}} + \sqrt{6}\,\frac{\eta'_\psi}{f_{\rm d}}\right)}_{SU(3)_{\rm diag}\ \text{Instantons at conf.}} + \underbrace{\Lambda^4_{\rm QCD}\,\cos\left(2\,\frac{\eta'_{\rm QCD}}{f_\pi} + \sqrt{6}\,\frac{\eta'_\psi}{f_{\rm d}}\right)}_{SU(3)_{\rm c}\ \text{Instantons at conf.}}$$

$$M^2_{\eta'_\chi,\,\eta'_\psi,\,\eta'_{\rm QCD}} = \begin{pmatrix} 4\,\frac{\left(\Lambda^4_{\rm SSI}+\Lambda^4_d\right)}{f^2_{\rm d}} & 2\sqrt{6}\,\frac{\Lambda^4_d}{f^2_d} & 0 \\ 2\sqrt{6}\,\frac{\Lambda^4_d}{f^2_d} & 6\,\frac{\left(\Lambda^4_d+\Lambda^4_{\rm QCD}\right)}{f^2_{\rm d}} & 2\sqrt{6}\,\frac{\Lambda^4_{\rm QCD}}{f_\pi\,f_{\rm d}} \\ 0 & 2\sqrt{6}\,\frac{\Lambda^4_{\rm QCD}}{f_\pi\,f_{\rm d}} & 4\,\frac{\Lambda^4_{\rm QCD}}{f^2_\pi} \end{pmatrix}$$

arXiv:1805.06465

Dynamical axion masses



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Solution to the Strong CP problem

- ➔ Any source of axion mass breaks the PQ symmetry, **do SSI spoil the Strong CP solution?**
- ➔ Breaking pattern imposes:

$$\mathcal{L} \supset \bar{\theta}_6 \frac{\alpha_6}{8\pi} G_6 \tilde{G}_6 + \bar{\theta}' \frac{\alpha'}{8\pi} G' \tilde{G}' \longrightarrow (\bar{\theta}_6 + \bar{\theta}') \frac{\alpha_{\rm diag}}{8\pi} G_{\rm diag} \tilde{G}_{\rm diag} + \bar{\theta}_6 \frac{\alpha_c}{8\pi} G_c \tilde{G}_c$$

- ➔ Therefore the potential reads:

$$\mathcal{L}_{eff} = \Lambda^4_{\rm SSI} \cos\left(-2\frac{\eta'_\chi}{f_{\rm d}} + \bar{\theta}'\right) + \Lambda^4_{\rm diag} \cos\left(-2\frac{\eta'_\chi}{f_{\rm d}} - \sqrt{6}\frac{\eta'_\psi}{f_{\rm d}} + \bar{\theta}' + \bar{\theta}_6\right) + \Lambda^4_{\rm QCD} \cos\left(-\sqrt{6}\frac{\eta'_\psi}{f_{\rm d}} + \bar{\theta}_6\right)$$

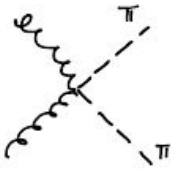
- ➔ The alignment of the 3 terms in the potential result in a CP-conserving minimum

$$\left\langle \bar{\theta}' - 2\frac{\eta'_\chi}{f_{\rm d}} \right\rangle = 0\,, \qquad \left\langle \bar{\theta}_6 - \sqrt{6}\frac{\eta'_\psi}{f_{\rm d}} \right\rangle = 0$$

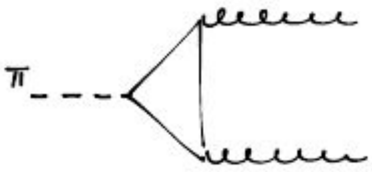
Strong CP problem solved

Low energy Spectrum and Phenomenology

- ➔ No light axion.
  - ◆ Both axions too heavy for colliders
- ➔ Sterile fermions ψ_ν with couplings suppressed by Λ_{CUT} (basically invisible)
- ➔ QCD Coloured "axipions" are collider accessible, octets:



Pair produced



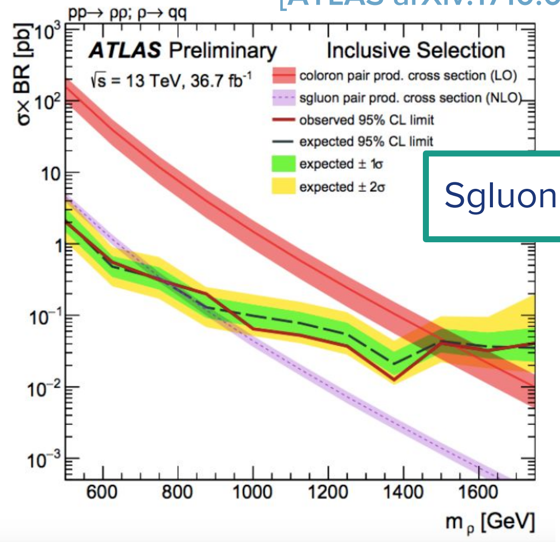
Anomalous decay

$$m(8_c) \gtrsim 770\, GeV$$

$$m^2(8_c) \approx \frac{9\alpha_c}{4\pi}\Lambda^2_{\rm diag}$$

$$\Lambda_{\rm diag} \gtrsim 3\,\mathrm{TeV}$$

[ATLAS arXiv:1710.07171]



Sgluon search

arXiv:1805.06465

Conclusions

- Strong CP problem solved with **massless quarks** and **unification.**

$$SU(6) \times SU(3') \xrightarrow{\Lambda_{\text{CUT}}} SU(3)_c \times SU(3)_{\text{diag}}$$

- Unified partners of the SM quarks are **successfully decoupled**.
- New gauge group confines the massless quarks into heavy bound states O(TeV).
- Small size instantons provide a new source of axion mass:
  - No light axion results.
- The three scales $\Lambda_{\text{CUT}} \gg \Lambda_{\text{diag}} \gg \Lambda_{\text{QCD}}$ are naturally separated by the running.
- Most promising collider signals come from the exotic pion color octet.

Thank you!