A common solution to the hierarchy and strong CP problems via composite dynamics

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Outline

Brief introduction to the hierarchy and strong CP problems

Motivation

An example model and its properties

Conclusions and Outlook

The strong CP problem

$$\mathcal{L}_{\text{QCD}} \supset \theta \frac{g_s^2}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu} + \sum_q \bar{q} m_q e^{i\theta_q} q, \qquad |\bar{\theta}| = |\theta + \theta_q| < 10^{-10}$$

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$$\mathcal{L}_a \supset \left(\frac{a}{f_a} + \bar{\theta} \right) \frac{g_s^2}{32\pi^2} G \tilde{G}$$

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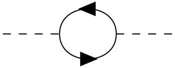
The strong CP problem is dynamically solved

$$\left\langle \frac{a}{f_a} + \bar{\theta} \right\rangle = 0, \qquad m_a^2 f_a^2 \simeq \Lambda_{\text{QCD}}^4$$

The hierarchy problem

$$\mathcal{L} \supset m_H^2 |H|^2, \quad \Delta m_H^2 \approx \Lambda_{\mathrm{NP}}^2$$



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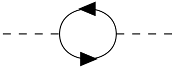

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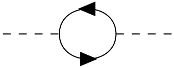

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Composite Higgs models (CHMs)

The Higgs is a pseudo-Nambu-Goldstone boson (pNGB) and its mass is protected by symmetry.

- New fermions, ω, and new strong interaction, *hypercolor* (HC)
- New global symmetry G, spontaneously broken to H

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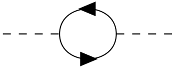

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QCD analogy

$$G_F = SU(3)_L \times SU(3)_R$$
$$\downarrow \langle q_L q_R \rangle$$
$$H_F = SU(3)_V$$
$$\dim[G_F] - \dim[H_F] = 8$$
$$\Rightarrow \pi^0, \pi^\pm, K^0, \bar{K}^0, K^\pm, \eta$$

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Open up the parameter space com-
pared to standard QCD axion models

Model setup

Recipe

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Ensure that $\bar{\theta}_c = \bar{\theta}_{sp}$	$\longrightarrow$	Embedd both color and grand-color in the same gauge group

Model setup

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Ensure that $$\left\langle \frac{a}{f_a} + \bar{\theta}_{c,sp} \right\rangle = 0$$	$\longrightarrow$	Minimize the axion potential and look for potential CP violating sources

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Give mass to the SM fermions	→	Top partners
Study the pNBGs potential	→	Spurion analysis to include all sources of explicit symmetry braking

The gauge group

$$\mathcal{G}_{\text{HC}} \times SU(2N_{GC}+3) \times SU(2)_L \times U(1)_{Y'}$$

$$\Lambda_{\text{GC}} \Big\downarrow \langle\Phi\rangle, \langle\Xi\rangle$$

$$\mathcal{G}_{\text{HC}} \;\times\; Sp(2N_{GC}) \;\times\; SU(3)_C \;\times\; SU(2)_L \;\times\; U(1)_Y$$

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$$\boxed{\mathcal{G}_{\text{HC}}} \times \boxed{Sp(2N_{GC})} \times \boxed{SU(3)_C \times SU(2)_L \times U(1)_Y}$$

- $\mathcal{G}_{\text{HC}}$ → Strong hypercolor group for composite Higgs and axion
- $Sp(2N_{GC})$ → New hidden strong sector to increase axion mass
- $SU(3)_C \times SU(2)_L \times U(1)_Y$ → SM

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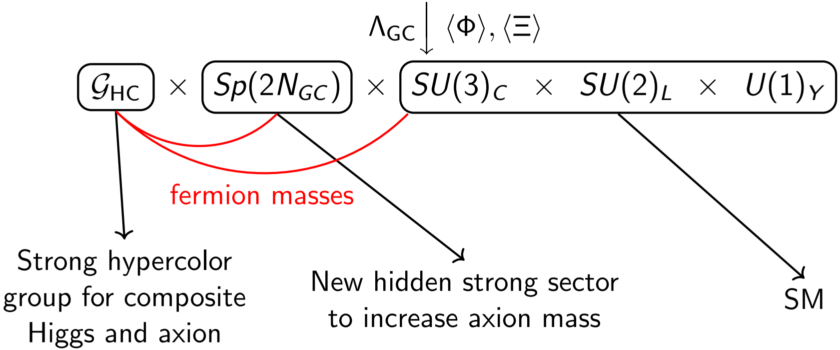

The meson resonances

Extremely rich field content

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Numerous (broken) global symmetries
$\downarrow$
many Goldstone bosons

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Additional gauge singlets

that mix with the axion, η

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pNGBs potential and spurion analysis

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Write down most general Lagrangian that respect both *gauge* and *global* symmetries

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Axion vev?

$\rightarrow$ Numerically verified to be zero

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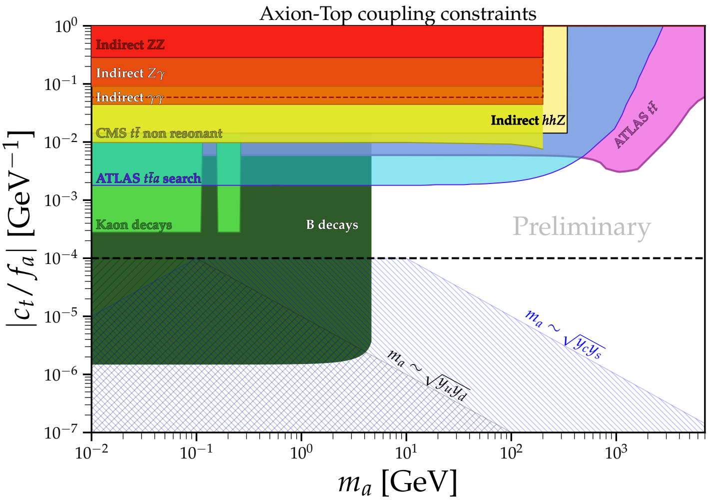
Other CP violating sources under control

$$y_{\psi_1} y_{\psi_2} \frac{1\text{TeV}^4}{f_a^2} \lesssim m_a^2 \lesssim y_{\psi_1} y_{\psi_2} f_a^2$$



[Esser, Madigan, Sanz, Ubiali, 2303.17634]
[Esser, Madigan, Salas-Bernardez, Sanz, Ubiali, 2404.08062]

Conclusions and Outlook

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Thanks for the attention!

Backup slides

The field content

	$SO(N_{HC})$	$Sp(2N_{GC})$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$Q_L = \begin{pmatrix} q_L \\ \psi_q \end{pmatrix}$	$\mathbf{1}$	$\mathbf{1}$	$\square$	$\mathbf{2}$	$\frac{1}{6}$
	$\mathbf{1}$	$\square$	$\mathbf{1}$	$\mathbf{2}$	0
$U_R = \begin{pmatrix} u_R \\ \psi_u \end{pmatrix}$	$\mathbf{1}$	$\mathbf{1}$	$\square$	$\mathbf{1}$	$-\frac{2}{3}$
	$\mathbf{1}$	$\square$	$\mathbf{1}$	$\mathbf{1}$	$-\frac{1}{2}$
$D_R = \begin{pmatrix} d_R \\ \psi_d \end{pmatrix}$	$\mathbf{1}$	$\mathbf{1}$	$\square$	$\mathbf{1}$	$\frac{1}{3}$
	$\mathbf{1}$	$\square$	$\mathbf{1}$	$\mathbf{1}$	$\frac{1}{2}$

The field content

	$SO(N_{\mathrm{HC}})$	$SU(2N_{\mathrm{GC}}+3)$	$SU(2)_{\mathrm{L}}$	$U(1)_{\mathrm{Y'}}$
$\omega_{1,2}$	**Spin**	$\mathbf{1}$	$\mathbf{2}$	0
ω_3	**Spin**	$\mathbf{1}$	$\mathbf{1}$	$-\frac{1}{2}$
ω_4	**Spin**	$\mathbf{1}$	$\mathbf{1}$	$\frac{1}{2}$
χ	$\square$	$\square$	$\mathbf{1}$	x
$\bar{\chi}$	$\square$	$\bar{\square}$	$\mathbf{1}$	$-x$

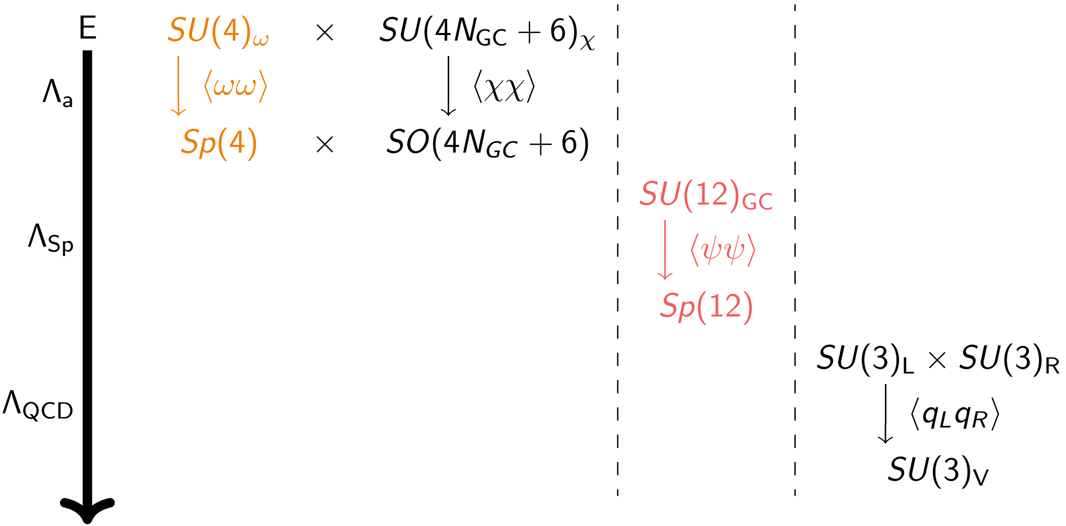
Possible gauge structures

$\mathcal{G}_{\mathcal{HC}}$	ω	χ	G_F/H_F
$Sp(2N_{HC})$	$4 \times \mathbf{F}$	$(4N_{GC}+6) \times \mathbf{A}_2$	$\frac{SU(4) \times SU(4N_{GC}+6) \times U(1)}{Sp(4) \times SO(4N_{GC}+6)}$
$SO(N_{HC})$	$4 \times \mathbf{Spin}$	$(4N_{GC}+6) \times \mathbf{F}$	

$SO(11)_{\mathrm{HC}}, SO(13)_{\mathrm{HC}}$

$3 \quad \leq \quad N_{\mathrm{GC}} \quad \leq \quad 6$

The different global symmetries



The meson resonances

	$SU(4)$	$Sp(4)$	names
$\langle\omega\omega\rangle$	$\mathbf{6}$	$\mathbf{1}$	σ_ω
		$\mathbf{5}$	π_ω
	$SU(4N_{GC}+6)$	$SO(4N_{GC}+6)$	names
$\langle\chi\chi\rangle$	$\mathbf{8N_{GC}^2+26N_{GC}+21}$	$\mathbf{1}$	σ_χ
		$\mathbf{8N_{GC}^2+26N_{GC}+20}$	π_χ
	$SU(12)$	$Sp(12)$	names
$\psi\psi$	$\mathbf{66}$	$\mathbf{1}$	σ_ψ
		$\mathbf{65}$	π_ψ

$$Sp(4) \supset SU(2)_L \times SU(2)_R$$
$$\pi_\omega \to \underbrace{(\mathbf{2},\mathbf{2})}_{H} \oplus \underbrace{(\mathbf{1},\mathbf{1})}_{\eta}$$

Higgs-like pions contained in π_ψ that mix with H

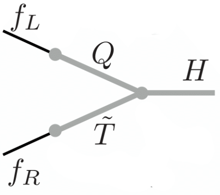
Additional gauge singlets that can mix with the axion, η

Partial Compositeness

Linear couplings between SM and HC fermions

$$\mathcal{L}_{int} \sim q\mathcal{O}_{lin}, \quad \mathcal{O}_{lin} = \left(\omega^T P_f \, \omega \, \chi\right)$$

$y_t =$



We need to study the **baryonic** resonances

Baryon	$SU(4) \times SU(4N_{GC}+6)$
$\omega\omega\chi$	$(\mathbf{4} \times \mathbf{4}, \Box) \to (\mathbf{6} \oplus \mathbf{10}, \Box)$
$\overline{\omega}\overline{\omega}\chi$	$(\bar{\mathbf{4}} \times \bar{\mathbf{4}}, \Box) \to (\mathbf{6} \oplus \overline{\mathbf{10}}, \Box)$
$\overline{\omega}\omega\overline{\chi}$	$(\bar{\mathbf{4}} \times \mathbf{4}, \overline{\Box}) \to (\mathbf{1} \oplus \mathbf{15}, \overline{\Box})$

$\to$ **not enough partners for all three generations**