A Colorful Mirror Solution to the Strong CP Problem

Claudio Andrea Manzari

UC Berkeley & Lawrence Berkeley National Laboratory

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Based on ArXiv:2303.06156 *Bonnefoy, Hall, C.A.M., Scherb*

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The Strong CP Problem

The Strong CP Problem is related to the presence of the lagrangian term

$$\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu}$$

This term violates P and T but conserves C, so it violates CP.

θ measures how badly is CP violated in strong interactions!

Including weak interactions, θ is shifted by the chiral transformation needed to diagonalize the quark mass matrix M

$$\mathcal{L} \supset \bar{\theta} \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} = \Big(\theta + \arg\det(M)\Big) \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

Note: There is no reason for θ and $\arg\det(M)$ to cancel.

Experimentally *How do we measure $\bar{\theta}$?*

$$d_n \simeq \frac{e\,\bar{\theta}\,m_q}{m_N^2} \quad \text{with} \quad |d_n| \leq 3 \times 10^{-26} e \cdot cm \Rightarrow \bar{\theta} \lesssim 10^{-9}$$

Why is $\bar{\theta}$ so small ?

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Approaches

The Massless up-quark

The SM has an additional gloabl chiral $U(1)$ symmetry, $m_u = 0$.

$$u \to e^{i\alpha\frac{\gamma_5}{2}} u \implies \theta \to \theta + \alpha$$

$\bar{\theta}$ become unphysical!

Lattice results seem to disfavor this possibility.

The Axion

Introducing a global chiral $U(1)$ symmetry, spontaneously broken.

$$\mathcal{L} \supset \left(\frac{a}{f_a} + \bar{\theta}\right) G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu}$$

The axion dynamically drives the CP violating term in the QCD Lagrangian to zero.

P or CP

P or CP are symmetries of nature.

$$\bar{\theta} = 0$$

They must be spontaneously broken! Phys.Rev.D 41,1286, Phys.Rev.Lett.62.1079, PhysRevLett.67.2765, JHEP09(2021)130, JHEP07(2019)016.

Parity & The Mirror World

We double the full SM and impose Parity ArXiv:2303.06156

Let me show you how this idea arises naturally.

We start with $SU(3)_X \times SU(3)_Y$:

$$\mathcal{L} \supset g_X^2 \theta_X \, X^{a\,\mu\nu} \tilde{X}^a_{\mu\nu} + g_Y^2 \theta_Y \, Y^{a\,\mu\nu} \tilde{Y}^a_{\mu\nu}$$

We now break them to the diagonal subgroup $SU(3)_{\rm QCD}$:

$$\mathcal{L} \supset \frac{g_X^4 \theta_X + g_Y^4 \theta_Y}{g_X^2 + g_Y^2} \, G_H^{a\,\mu\nu} \tilde{G}^a_{H\,\mu\nu} + \underbrace{\frac{g_X^2 g_Y^2}{g_X^2 + g_Y^2}}_{g_S^2} \underbrace{(\theta_X + \theta_Y)}_{\theta_{\rm QCD}} \, G_{SM}^{a\,\mu\nu} \tilde{G}^a_{SM\,\mu\nu}$$

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The Mirror World

$\mathrm{P} \circ \mathbb{Z}_2$ exchanges the SM and mirror fields:

$$SU(3)_X \times SU(2) \times U(1)_Y \leftrightarrow SU(3)' \times SU(2)' \times U(1)_{Y'}$$

$$\mathcal{L} \supset \bar{\theta} \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \bar{\theta}' \frac{g_s^2}{32\pi^2} G'^{\,a}_{\mu\nu} \tilde{G}'^{\,a\mu\nu}$$

$$\mathrm{P} \circ \mathbb{Z}_2 : \qquad Y_{u'} = Y_u^{\dagger\,*}\,, \quad Y_{d'} = Y_d^{\dagger\,*}\,, \quad g = g'\,, \quad \theta = -\theta'$$

Below the Breaking Scale of $SU(3) \times SU(3)' \to SU(3)_{\mathrm{QCD}}$: $\bar{\theta}_{\mathrm{QCD}} = \bar{\theta} + \bar{\theta}' = 0$

$^* \Rightarrow \arg\det Y'_u Y'_d = -\arg\det Y_u Y_d$

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Parity Breaking

Experimental observations rule out the possibility that P is unbroken!

$$v' \gg v$$

- Dangerous classical corrections* (dim-6 Operators):

$$\frac{g_3^2 \mathrm{Tr} G\tilde{G}}{16\pi^2 M_P^2}\left(\lambda |H|^2 + \lambda' |H'|^2\right) - \left(g_3, G, H \leftrightarrow g_3', G', H'\right)$$

$$\Rightarrow \bar{\theta}_{\mathrm{QCD}} = (\lambda - \lambda')(v^2 - v'^2)/M_P^2$$

- Quantum corrections: model dependent! In the following scenarios similar to the SM, under control.

* These are Model-Independent Constraints

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Color Breaking

How do we break $SU(3) \times SU(3)' \to SU(3)_{\text{QCD}}$?

Bi-fundamental Scalar Σ

$$\Sigma \begin{cases} \xrightarrow{(\mathbf{3},\mathbf{3})} U\Sigma U'^T \\ \xrightarrow{(\mathbf{3},\bar{\mathbf{3}})} U\Sigma U'^\dagger \end{cases}$$

$$V(\Sigma) = -m^2 \mathrm{Tr}(\Sigma\Sigma^\dagger) + c\,\mathrm{Tr}^2(\Sigma\Sigma^\dagger) + \tilde{c}\,\mathrm{Tr}(\Sigma\Sigma^\dagger)^2 + \left(\tilde{m}\det(\Sigma) + h.c.\right)$$

The unbroken gauge symmetry in the global minimum is $U(1)^2$, $SU(2)^2 \times U(1)$ or $SU(3)$. PhysRevD.97.055024

Composite Models

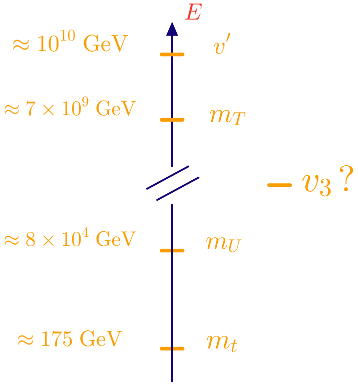
	$SU(N)$	$SU(3)$	$SU(3)'$
ψ_L	$\mathbf{N}$	$\mathbf{3}$	$\mathbf{1}$
ψ_R	$\mathbf{N}$	$\mathbf{1}$	$\mathbf{3}'$

$$\langle \bar{\psi}_L \psi_R \rangle = v_3^3 \mathbf{1}_{3\times 3}$$

More on this after the talk if you like!

Energy Scales of the Model

We have a model with two scales: v' and v_3.



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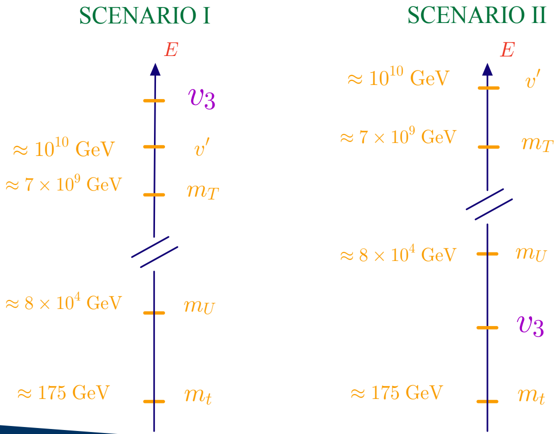
Energy Scales of the Model



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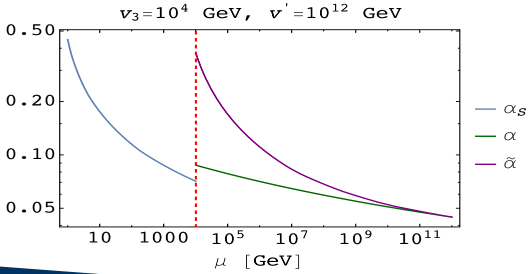
Higgsing $SU(3) \times SU(3)'$ - Bounds

- **Collider Bounds:**
  - The lightest mirror-quarks are stable $\Rightarrow$ bound states with charge $\pm 1/3, \pm 2/3, \pm 4/3$
    ATLAS search for stable gluinos and charginos $\Rightarrow m_{u'} \gtrsim 1.3\ \text{TeV}$ ArXiv2205.06013
  - Massive vector octet coupled to (mirror) quarks and QCD gluons, as well as various scalar states. Bounds depend on v_3 and v' PhysRevD.97.055024 JHEP04(2018)114

- **Running of α:**

  $SU(3)'$ cannot confine above v_3



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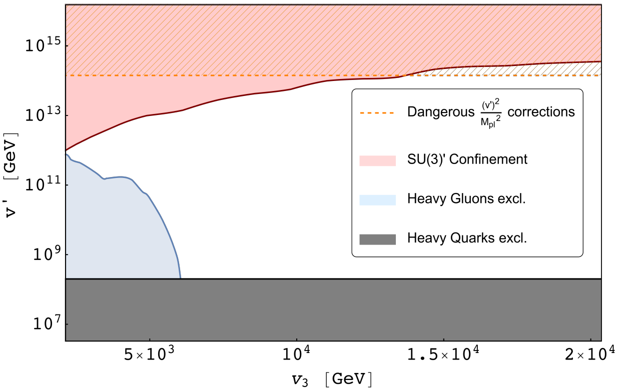

Conclusions

- I discussed a solution to the strong CP problem based on restoring P(CP) as a symmetry of nature in the UV.

- The novelty of our framework is the doubling of $SU(3)$ which leads to a different mechanism:
  - Parity is important to get $\bar{\theta} = -\bar{\theta}'$.
  - $SU(3) \times SU(3)' \to SU(3)_{\rm QCD}$ sets $\bar{\theta}_{\rm QCD} = 0$.

- The scenario where $v_3 \ll v'$ has a rich and interesting phenomenology:
  - Testable at collider.
  - May have DM candidates.
  - Phase transitions...

Thank you for the attention!

Backup Slides

The Strong CP Problem

Historical Introduction

The QCD Lagrangian with N flavors has a large global symmetry $U(N)_V \times U(N)_A$ symmetry in the limit of vanishing quark masses.

$$m_u\, , m_d \ll \Lambda_{QCD} \implies U(2)_V \times U(2)_A \quad \text{EXPECTED}$$

EXPERIMENTALLY

$$U(2)_V = SU(2)_I \times U(1)_B \implies \text{hadron multiplets}$$

$$U(2)_A \quad \text{broken by quark condensate } \langle \bar{q} q \rangle$$

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We expect four Nambu-Goldstone bosons associated with the breaking of $U(2)_A$.
EXPERIMENTALLY

$$m_\pi^+ \sim m_\pi^- \sim m_\pi^0 \sim 0 \quad \text{but} \quad m_\eta \gg m_\pi!$$

This was dubbed the $U(1)_A$ problem *Weinberg, Phys.Rev.D11,3583(1975)3*

Solution to the $U(1)_A$ problem

$U(1)_A$ is anomalous with QCD, such that

$$\partial_\mu J_5^\mu = \frac{g_s^2 N}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu} \quad \text{with} \quad J_5^\mu = \bar{\psi}\gamma^\mu\gamma_5\psi$$

Hence

$$q \to e^{i\alpha\frac{\gamma_5}{2}} q \implies \delta S = \alpha \frac{g_s^2 N}{32\pi^2} \int dx^4 G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu}$$

't Hooft showed that there are gauge configuration for which $\delta S \neq 0 \implies U(1)_A$ is not a symmetry of QCD!

Quantum Corrections to $\bar{\theta}$

We need to check that the spontaneous breaking of parity does not contribute through large loop corrections to $\bar{\theta}_{\text{QCD}}$.

- $\langle\Sigma\rangle$, $\langle H\rangle$, $\langle H'\rangle$ can always be chosen real and do not introduce CP phases ✓
- The sources of CP violation are fully contained in the Yukawas:
  - Above v_3: $Y_u' = Y_u^\dagger \implies$ only one phase!,
  - Below v_3: the Yukawas run differently.

Both cases similar to the SM: no contribution before three-loop order. ✓

Nucl.Phys.B150.1979

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Quantum Corrections to $\bar{\theta}$

Contributions to $\bar{\theta}$ come from 2-point function of fermions.

$$\sum_{j} V_{ij} V_{ij}^{*} = 1$$

$$\sum_{j\,k\,l} V_{ij} V_{kj}^{*} V_{kl}^{*} V_{il}^{*}$$

These sum to 0.

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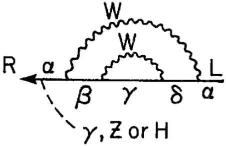

First non-zero finite imaginary contributions. No divergent contributions below 7-loop.

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Quantum Corrections to $\bar{\theta}$

In the SM

$$\Delta\bar{\theta} = \left(\frac{\alpha}{\pi}\right)^2 s_1^2 s_2 s_3 \sin\delta \, \frac{m_s^2 m_c^2}{m_W^4} \sim 10^{-16}$$

$$e_n \sim 10^{-28} \text{ cm}$$

Energy Scales of the Model

- Scenario I: $v_3 \sim v'$
  - $\bar{\theta}_{\rm QCD}$ is set to 0 in the UV and run down as in the SM.
  - Heavy Gluons can be integrated out in the UV.
  - in the IR the model looks like L-R symmetric models with two $U(1)$.

- Scenario II: $v_3 \ll v'$
  - $\bar{\theta}_{\rm QCD}$ is set to 0 in the IR.
  - $\bar{\theta}$ and $\bar{\theta}'$ run differently above v_3. Negligible effect (see below).
  - Rich and Novel Phenomenology.