

Addressing the CP-strong problem with two heavy axions

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The Strong CP Problem

The θ − term in QCD

QCD allows a CP-violating term in the Lagrangian:

$$\mathcal{L} \supset \theta_{\text{eff}} \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

θ_{eff} is given by $\theta + \arg\det M$

Peccei-Quinn solution

Introduce a global $U(1)_{PQ}$ symmetry spontaneously broken at scale f_a. Its pseudo-Goldstone boson is the axion a:

$$\theta_{\text{eff}} \longrightarrow \theta + \frac{a(x)}{f_a}$$

Vacuum dynamics relaxes θ_{eff} to zero via the axion VEV

Experimental contraint

CP-violating observables in meson and baryon dynamics depend on θ_{eff}

$$d_n \lesssim 3 \times 10^{-26}\, e \cdot \text{cm} \implies |\theta_{\text{eff}}| \lesssim 10^{-10}$$

Why there is a so precise cancellation among the anomalous coupling to gluons and CP-violating weak phases is the **STRONG CP PROBLEM**

Axion mass and coupling

The axion mixes with QCD pNGB through an axial-anomaly like term

$$m_a^2 = \frac{2f_\pi^2}{f_a^2} m_\pi \frac{m_u m_d}{(m_u + m_d)^2} = 5.7\ \mu eV \left(\frac{10^{12} GeV}{f_a}\right)$$

The Quality Problem and the Heavy Axion

The quality problem

$U(1)_{PQ}$ is not protected by quantum gravity. Axion potential receives $\frac{f_a}{\Lambda_{Planck}}$ corrections

$$\delta\mathcal{L} \sim \frac{\varphi^n}{M_{\rm Pl}^{n-4}} \implies \delta\theta \sim \left(\frac{f_a}{M_{\rm Pl}}\right)^{n-4} \gg 10^{-10}$$

$$f_a \sim 10^{12}\ \text{GeV},\ n=5: \quad \delta\theta \sim 10^{-7} \gg 10^{-10}$$

A viable PQ symmetry must be "high quality“

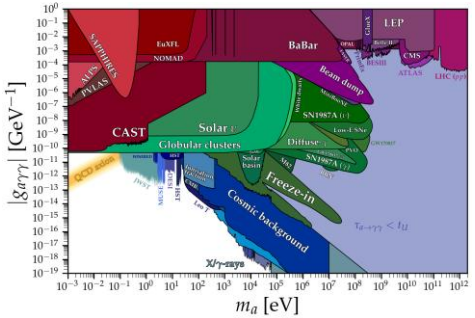
- Discrete symmetries
- Composite Axion
- Heavy Axion

The heavy axion solution

- Type equation here.Embedding of $SU(3)_c$ into the bigger gauge group $SU(11) \otimes Sp'(8) \to SU(3)_c \otimes Sp(8)$
- Two axions related to both coloured sectors
- They receive mass from $Sp(8)$ confinement scale f and $Sp'(8)$ instanton scale Λ_8

$$m_L = \frac{f^2}{f_a} \qquad m_H = \frac{\Lambda_8^2}{f_a}$$

New parameter space



Model Setup

$$G = SU(11) \otimes Sp'(8) \otimes SU(2)_L \otimes U(1)_{Y'} \otimes G_{discrete}$$

Field Content

Field	$SU(11)$	$Sp(8)'_{TC}$	$SU(2)_L$	$U(1)'_Y$	
Ψ_1	$\bar{11}$	1	1	$-6/11$	*SU(11) quarks*
Ψ_2	$\bar{11}$	1	1	$5/11$	
Ψ_3	11	1	2	$1/22$	
L	1	1	2	$-1/2$	*SM leptons*
$e^c{}_R$	1	1	1	1	
$\psi_{12}^{(\prime)}$	1	8	2	0	
$\psi_3^{(\prime)}$	1	8	1	$1/2$	*TC fermions*
$\psi_4^{(\prime)}$	1	8	1	$-1/2$	
$\Sigma^{(\prime)}$	11	8	1	$1/22$	
φ	1	1	1	0	*Scalars*
φ'	1	1	1	0	

Yukawa Interactions

Discrete symmetry

- Controls $\psi \leftrightarrow \psi'$ and $\Sigma \leftrightarrow \Sigma'$ mixing
- Restricts allowed Yukawa structures
- We examine $\boldsymbol{Z_4 \times Z_4 \propto Z_2}$ **group.** This requires the introduction of two singlet scalars ϕ and ϕ'

TC fermion Yukawa interactions

$$\mathcal{L} \supset Y\, \Psi(\Sigma\psi + \Sigma'\psi') + h.c.$$

Quark-TC fermion Yukawa interactions

$$\mathcal{L} \supset \mathrm{y}_{12}(\phi\psi_{12}\psi_{12} + \phi'\psi'_{12}\psi'_{12}) + \mathrm{y}_{34}(\phi\psi_3\psi_4 + \phi'\psi'_3\psi'_4) + h.c.$$

The $Z_4 \times Z_4 \ltimes Z_2$ group and the scalar potential

Quantum numbers

A double Dihedral group

Field	ψ	ψ'	Σ	Σ'	ϕ	ϕ'
$\mathbb{Z}_4 \times \mathbb{Z}_4$ charges	$(0,1)$	$(1,0)$	$(0,-1)$	$(-1,0)$	$(0,-2)$	$(-2,0)$

$$\rho(r) = \begin{pmatrix} e^{iq} & 0 \\ 0 & e^{iq'} \end{pmatrix} \qquad \rho(s) = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

- Each field carries two dihedral D_4 charges
- $\rho(r)$ and $\rho(s)$ generate the group

Constraining the Yukawa structure

$$Y\Psi(\Sigma\psi + \Sigma'\psi') + y(\phi\psi\psi + \phi'\psi'\psi')$$

Scalar Potential

$\Sigma - \Sigma' - \phi - \phi'$ interactions

$$V_\phi(\phi, \phi') = -\lambda(\phi^2 - \mu^2)^2 - \lambda(\phi'^2 - \mu^2)^2 + 2\xi\phi^2\phi'^2$$

$$\begin{aligned} V_\Sigma(\Sigma,\ \Sigma') = &- m^2 \mathrm{Tr}[\Sigma^\dagger\Sigma + \Sigma'^\dagger\Sigma'] + \lambda_1(\mathrm{Tr}^2[\Sigma^\dagger\Sigma] + \mathrm{Tr}^2[\Sigma'^\dagger\Sigma']) + \lambda_2 \mathrm{Tr}[\Sigma^\dagger\Sigma]\mathrm{Tr}[\Sigma'^\dagger\Sigma'] \\ &+ \lambda_3 |\mathrm{Tr}[\Sigma^\dagger\Sigma']|^2 + \lambda_5 \mathrm{Tr}[\Sigma^\dagger\Sigma\Sigma^\dagger\Sigma + \Sigma'^\dagger\Sigma'\Sigma'^\dagger\Sigma'] \\ &+ \lambda_6 \mathrm{Tr}[\Sigma^\dagger\Sigma\Sigma'^\dagger\Sigma'] + \lambda_7 \mathrm{Tr}[\Sigma^\dagger\Sigma'\Sigma'^\dagger\Sigma] \end{aligned}$$

$$V_{\phi\Sigma} = \rho(\mathrm{Tr}[\Sigma^\dagger\Sigma](\phi^2 + \phi'^2) + \mathrm{Tr}[\Sigma'^\dagger\Sigma'](\phi^2 + \phi'^2))$$

VEV structure

$$\langle\Sigma\rangle = \begin{pmatrix} 0_{3\times8} \\ v_\Sigma 1_8 \end{pmatrix} \qquad \langle\Sigma'\rangle = \begin{pmatrix} 0_{3\times8} \\ 0_{8\times8} \end{pmatrix} \qquad \langle\phi\rangle = v_\phi \qquad \langle\phi'\rangle = 0$$

$$v_\phi \gg v_\Sigma \qquad \lambda > 2\xi$$

Fermion and Scalar mass spectrum

Fermion mass spectrum

The mass matrix

$$M_{\psi\psi'\Psi} = \begin{pmatrix} 0 & Yv_\Sigma & 0 \\ Yv_\Sigma & yv_\phi & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Approximate eigenvalues

$$m_\Psi \approx Yv_\Sigma \qquad m_\psi \approx yv_\phi \qquad m_{\psi'} = 0$$

- ψ' stay massless and condense at μ_C
- Ψ have mass of fractions (v_Σ/v_ϕ) of v_Σ
- ψ are the heaviest

Scalar mass spectrum

$\phi - \phi'$ masses

$$m_\phi = -8\lambda\mu^2 + 16\rho v_{II}^2 \qquad m_{\phi'} = 2\mu^2(\xi + 2\lambda) + 16\rho v_{II}^2$$

- ϕ mass is at v_ϕ
- ϕ' mass can be at the condensation scale of ψ'
- ϕ' is dynamical all above the gauge breaking scale, ϕ is not

$\Sigma - \Sigma'$ masses

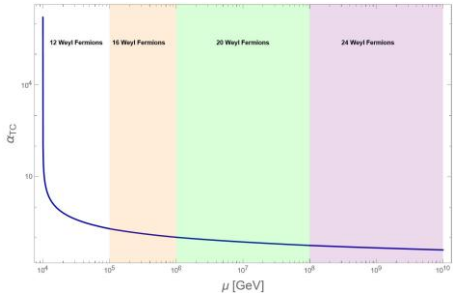
$$\Sigma = \begin{pmatrix} (h_u)_{3\times8} \\ (v_{II} + h_d)_{8\times8} \end{pmatrix} \quad \Sigma' = \begin{pmatrix} (h'_u)_{3\times8} \\ (h'_d)_{8\times8} \end{pmatrix}$$

- Goldstone boson directions in Σ are eaten by gauge bosons
- ${h_u}'$ masses at the condensation scale. They will be used for FPC.
- All other scalars decouple around v_Σ

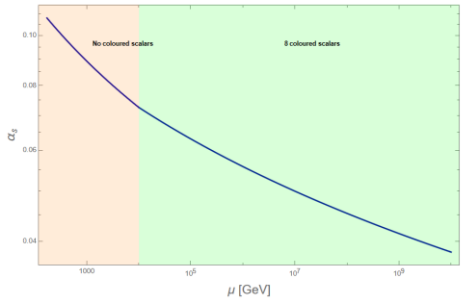
The game of the coupling constants

TCcoupling α_{TC} and QCDcoupling α_s

α_{TC}



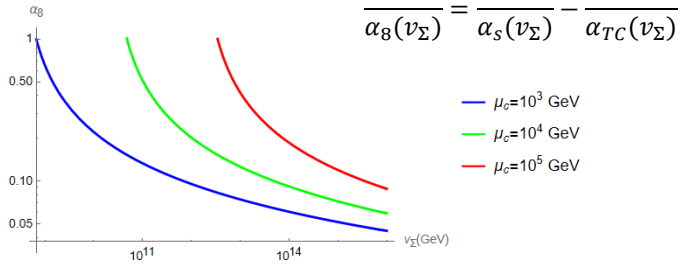
α_s



$Sp(8)'$coupling α_8

α_8

$$\frac{1}{\alpha_8(v_\Sigma)} = \frac{1}{\alpha_s(v_\Sigma)} - \frac{1}{\alpha_{TC}(v_\Sigma)}$$



- α_8 enters the instantonic potential computation
- Smallness is required for Dilute Gas Approximation
- A wide choice μ_c and v_Σ is possible

The $Sp(8)'$ instantonic dynamics

The small instanton approximation

Instanton Density

$$D_8[\alpha_8] = \frac{0.466 e^{-1.679\times 5}}{(5-1)!(5-2)!}\left(\frac{2\pi}{\alpha_8}\right)^{10} e^{-\frac{2\pi}{\alpha_8}}$$

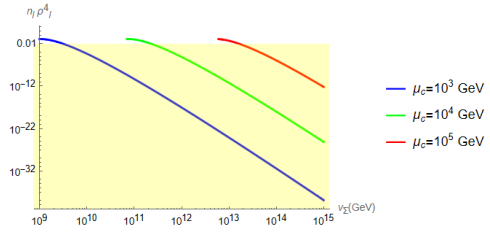
($k_{Sp(8)'}$)

- $k_{Sp(8)'}$ is a group dependent factor
- We put $k_{Sp(8)'} = k_{SU(5)}$

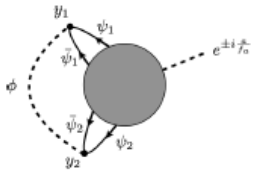
Dilute Gas Approximation (DGA)

$$\left(\frac{2\pi}{\alpha_8}\right)^{10} \ll e^{\frac{2\pi}{\alpha_8}}$$

$$\alpha_8 < 0.168$$

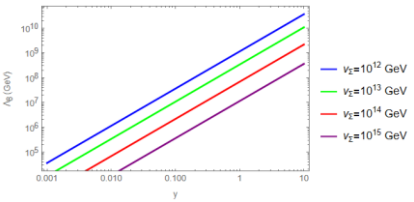


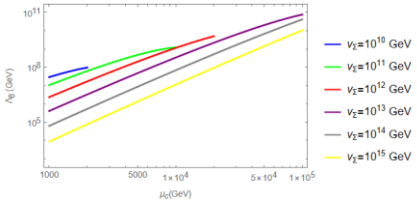
The small instanton scale



$$\Lambda_8^4 = \frac{2v_\Sigma^4}{b_8' - 4}\frac{0.466 e^{-1.679\times 5}}{(5-1)!(5-2)!}\left(\frac{y}{4\pi}\right)^6\left(\frac{2\pi}{\alpha_8(v_\Sigma)}\right)^{10} e^{-\frac{2\pi}{\alpha_8(v_\Sigma)}}$$

- Λ_8 is related to the heavy axion mass
- The model is designed to have only a power-6 Yukawa suppression





The pNGB-axion dynamics

The breaking pattern of the global symmetry

$SU(12) \to Sp(12)$

$$\Pi_{vac} = \begin{pmatrix} i\sigma_2 e^{i\phi_1} & 0 & 0 & 0 & 0 & 0 \\ 0 & i\sigma_2 e^{i\phi_2} & 0 & 0 & 0 & 0 \\ 0 & 0 & i\sigma_2 e^{i\phi_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & i\sigma_2 e^{i\phi_4} & 0 & 0 \\ 0 & 0 & 0 & 0 & i\sigma_2 e^{i\phi_5} & 0 \\ 0 & 0 & 0 & 0 & 0 & i\sigma_2 e^{i\phi_6} \end{pmatrix} \qquad y_{TC} = \mathrm{diag}(y_1, y_2, y_3, y_4, y_5, y_6) \otimes i\sigma_2$$

$$\Pi = e^{i\frac{\eta'_{TC}}{4\sqrt{3}f}} e^{i\frac{i}{f}\sum_{a=1}^{65}\pi_a X^a} \Pi_{vac}$$

- The vacumm is parametrized in terms of 6 phases
- Unitary rotations among isospin doublets and singlets can used to put the Yukawa couplings in an antisymmetric real matrix
- The dynamics is described in terms of 65 pNGB and a singlet direction $\eta_{TC}{}'$

The pNGB+axion potential

$$\begin{aligned} V_\Pi = &- c_1 f^4 \mathrm{Tr}(y_{TC}\Pi y_{TC}\Pi + \Pi^\dagger y_{TC}^\dagger \Pi^\dagger y_{TC}^\dagger) - c_2 f^4 [\mathrm{Tr}(y_{TC}\Pi + \Pi^\dagger y_{TC}^\dagger)]^2 \\ &+ \frac{a_t f^2}{4}[\bar\theta_{11} + \bar\theta_8 - \frac{i}{2}\mathrm{Tr}(\log\Pi - \log\Pi^\dagger)]^2 - \Lambda_8^4 \cos\bar\theta_8 \\ &- c_3 f^3 \phi' \mathrm{Tr}(y_{TC}\Pi + \Pi^\dagger y_{TC}^\dagger) + V_\Sigma(\Sigma,\Sigma') + V_\phi(\phi,\phi') + V_{\phi\Sigma}(\phi,\phi',\Sigma,\Sigma') \end{aligned}$$

$$\begin{aligned} E_{vac} = &\frac{a_t f^2}{4}[\bar\theta_{11} + \bar\theta_8 - 2\sum_{i=1}^{6}\phi_i]^2 - 4c_1 f^4 \sum_{i=1}^{6} y_i^2 \cos(2\phi_i) - 16 c_2 f^4 [\sum_{i=1}^{6}\cos(\phi_i)]^2 \\ &+ 4c_3 f^3 v_{\phi'} \sum_{i=1}^{6} y_i \cos(\phi_i) + V_\phi(v_\phi, v_{\phi'}) + V_\Sigma(v_\Sigma, 0) + V_{\phi\Sigma}(v_\phi, v_{\phi'}, v_\Sigma, 0) \end{aligned}$$

$$f_{PQ} \gg \sqrt{a_t} \gg \mathrm{f}$$

- We find a CP-conserving solution with zero vacuum phase and each axion relaxing to zero one θ-angle
- ϕ' adquires a VEV at the condensation scale due to the tadpole interaction with the condensate

The pNGB-axion dynamics

Axion mass matrix

Effective vacuum phases

$$\phi_k = \frac{1}{2\, y_k \left(c_1 y_k + 2c_2 \mathcal{A} + c_3^2 \mathcal{A}\right) \mathcal{K}} \left(\theta_{11} + \theta_8 - \frac{a_{11}}{f_{11}} - \frac{a_8}{f_8}\right) \qquad \mathcal{A} = \sum_{i=1}^{6} y_i \qquad \mathcal{K} = \sum_{k=1}^{6} \frac{1}{y_k \left(c_1 y_k + 2c_2 \mathcal{A} + c_3^2 \mathcal{A}\right)}$$

- After substituting, we obtain the effective lagrangian for the axions
- Axions do not mix with neutral pNGB but η'_{TC}
- η'_{TC} decouples at the scale $\sqrt{a_t}$ higher than axion masses

Axion masses

$$a_L = \frac{a_{11} + a_8}{\sqrt{2}}, m_L^2 = \frac{4\, f^4}{f_{PQ}^2 K} \qquad a_H = a_8, m_H^2 = \frac{\Lambda_8^4}{f_{PQ}^2}$$

pNGB mass matrix

Masses from strong dynamics

$$m_{II}^2 = 6 y_0^2 f^2 \left(c_1 + 16 c_2 + 8 c_3^2\right)$$

- The result is given in the degenerate Yukawa limit
- pNGB are lifted at the condensation scale

Masses from gauge boson loop

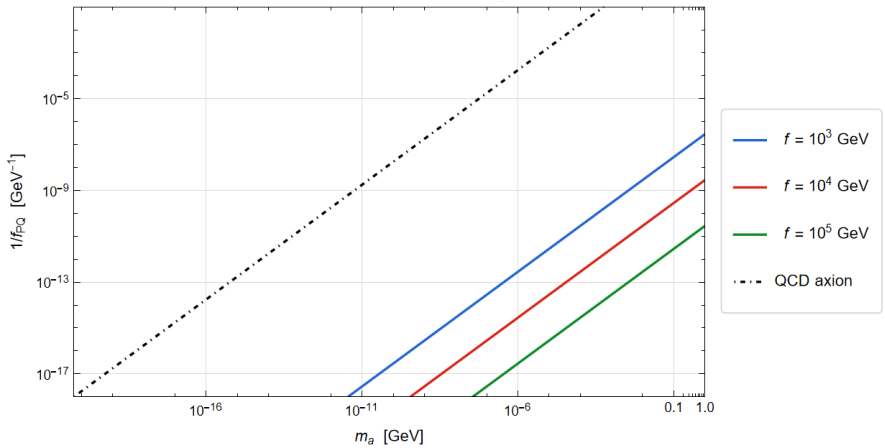
Sector	$(SU(2)_L, Y)$	$SU(3)_{gen}$	NGBs
$[\psi_3\psi_3] + [\psi_4\psi_4]$	$(1, \pm 2y)$	$\mathbf{3}$	$3+3=6$
$[\psi_3\psi_4]_{\mathbf{8}}$	$(1, 0)$	$\mathbf{8}$	8
$[\psi_3\psi_{12}] + [\psi_4\psi_{12}]$	$9 \times (\mathbf{2}, +\frac{1}{2})$ complex	$\mathbf{3} \otimes \mathbf{3}$	36
$[\psi_{12}\psi_{12}]_{\mathbf{1}_{SU(2)}}$	$(1, 0)$	$\mathbf{6}_{\text{symm}}$	6
$[\psi_{12}\psi_{12}]_{\mathbf{3}_{SU(2)}}$	$3 \times (\mathbf{3}, 0)$	$\mathbf{3}_{\text{antisymm}}$	9
Charged total			51
Neutral total			14
Grand total			65

$$\Delta m^2_{\text{gauge}} = \kappa_g f^2 \left[g^2 C_2(\mathbf{R}) + g'^2 Y^2\right]$$

The pNGB-axion dynamics

Axion mass

The lightest axion

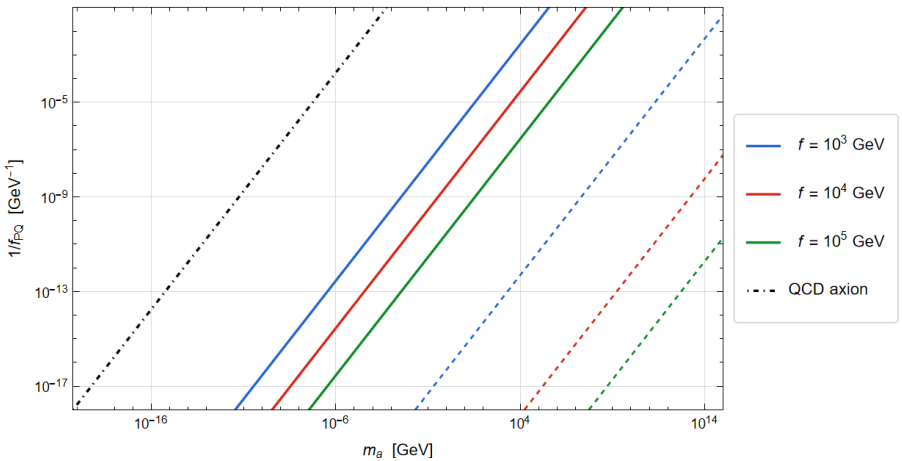


- The coloured lines show the squared axion mass $\frac{4\,f^4}{f_{PQ}^2 K}$ for different values of the condensation scale
- The dashed line show the squared QCD axion mass $\frac{\chi_{QCD}}{f_{PQ}^2}$ where $\chi_{QCD}^{1/4} = 75.5\ MeV$
- The axion mass can be enhanced up to the GeV scale
- The choice of the gauge symmetry breaking scale reduce the accessible region of f_{PQ} values

The pNGB-axion dynamics

Axion mass

The heaviest axion



- The dashed lines correspond to the heaviest axion
- A reference value $v_\Sigma = 10^{14} GeV$ has been used for the computation
- Mixing terms f^3/f_{PQ}^2 can make the interplay between the two eigenstates less trivial

Model Setup: A simple variation

$$G = SU(11) \otimes Sp'(8) \otimes SU(2)_L \otimes U(1)_{Y'} \otimes G_{discrete}$$

Field Content

Field	$SU(11)$	$Sp(8)'_{TC}$	$SU(2)_L$	$U(1)'_Y$	
Ψ_1	$\bar{11}$	1	1	−6/11	*SU(11) quarks*
Ψ_2	$\bar{11}$	1	1	5/11	
Ψ_3	11	1	2	1/22	
L	1	1	2	−1/2	*SM leptons*
${e^c}_R$	1	1	1	1	
${\psi_{12}}^{(')}$	1	8	2	0	
${\psi_3}^{(')}$	1	8	1	1/2	*TC fermions*
${\psi_4}^{(')}$	1	8	1	−1/2	
$\Sigma^{(')}$	11	8	1	1/22	
φ	1	1	1	0	*Scalars*

Yukawa Interactions

Discrete symmetry

- Controls ψ ↔ ψ′ and Σ ↔ Σ′ mixing
- Restricts allowed Yukawa structures
- We examine $G_{discr} = D_4 = \boldsymbol{Z_4 \propto Z_2}$ **group.**

TC fermion Yukawa interactions

$$\mathcal{L} \supset Y\, \Psi(\Sigma\psi + \Sigma'\psi') + h.c.$$

Quark-TC fermion Yukawa interactions

$$\mathcal{L} \supset y_{12}\phi(\psi_{12}\psi_{12} + \psi'_{12}\psi_{12}{}') + y_{34}\phi(\psi_3\psi_4 + \psi'_3\psi_4{}') + h.c.$$

The D_4 group and the scalar potential

Quantum numbers

A double Dihedral group

$$\rho(r) = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, \rho(s) = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

- We consider the bidimensional representation of D_4 generated by $\rho(r)$ and $\rho(s)$
- The transformations act on $\begin{pmatrix} \psi \\ \psi' \end{pmatrix}$ and $\begin{pmatrix} \Sigma \\ \Sigma' \end{pmatrix}$

Scalar Potential

VEV structure

$$\langle \Sigma \rangle = \begin{pmatrix} 0_{3\times 8} \\ v_\Sigma \mathbf{1}_8 \end{pmatrix}, \qquad \langle \Sigma' \rangle = 0, \qquad \langle \phi \rangle = v_\phi$$

$$v_\phi < v_\Sigma$$

Scalar Spectrum

$$\Sigma = \begin{pmatrix} (h_u)_{3\times 8} \\ (v_{II} + h_d)_{8\times 8} \end{pmatrix} \quad \Sigma' = \begin{pmatrix} (h'_u)_{3\times 8} \\ (h'_d)_{8\times 8} \end{pmatrix}$$

- Goldstone boson directions in Σ are eaten by gauge bosons
- $h_u{}'$ masses at the condensation scale. FPC.
- All other scalars decouple around v_Σ

Fermion spectrum and Instanton Dynamics

Fermion mass spectrum

The mass matrix

$$M_{\psi\psi'\Psi} = \begin{pmatrix} 0 & Yv_\Sigma & 0 \\ Yv_\Sigma & yv_\phi & 0 \\ 0 & 0 & yv_\phi \end{pmatrix}$$

Approximate eigenvalues

$$m_\Psi \approx v_\Sigma \qquad m_\psi \approx v_\Sigma \qquad m_{\psi'} = yv_\phi$$

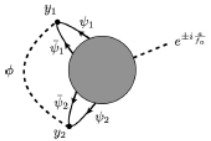
- ψ' acquires mass below v_Σ
- Ψ and ψ have mass of order v_Σ
- The stages of decoupling and running of α_{TC} show only minor variations

The small instanton scale

ϕ dynamics

- ϕ mass is at v_ϕ
- ϕ' mass is considered bigger than the condensation scale
- ϕ is dynamical all above the gauge breaking scale

Instanton scale



$$\Lambda_8^4 = \frac{2v_\Sigma^4}{b_8' - 4}\frac{0.466e^{-1.679\times5}}{(5-1)!(5-2)!}\left(\frac{y}{4\pi}\right)^{12}\left(\frac{2\pi}{\alpha_8(v_\Sigma)}\right)^{10}e^{-\frac{2\pi}{\alpha_8(v_\Sigma)}}$$

- There is a power 12 Yukawa suppression
- The small instanton scale shows an order 10 suppression

The pNGB-axion dynamics

The breaking pattern of the global symmetry

$SU(12) \to Sp(12)$

$$\Sigma_B = \begin{pmatrix} \Sigma_{B4} & & \\ & \Sigma_{B4} & \\ & & \Sigma_{B4} \end{pmatrix} \qquad \Sigma_{B4} \to \begin{pmatrix} i\sigma_2 e^{-i\phi_{12}} & 0 \\ 0 & -i\sigma_2 e^{i\phi_{34}} \end{pmatrix}$$

- From the TC mass degenaracy, we assume identical vacuum phases
- Unitary rotations among isospin doublets and singlets can used to put the mass matrix in an antisymmetric real matrix
- The dynamics is described in terms of 65 pNGB and a singlet direction $\eta_{TC}{}'$

The pNGB+axion potential

$$V_\Pi = \frac{a_t f^2}{4}[\bar{\theta}_{11} + \bar{\theta}_8 - \frac{i}{2}\,\mathrm{Tr}(\log\Pi - \log\Pi^\dagger)]^2 - \Lambda_8^4 \cos\bar{\theta}_8 - \frac{1}{2}C_m f^3 \mathrm{Tr}(M_{TC}\Pi + \Pi^\dagger M_{TC}^\dagger)$$

$$M_{TC} = \begin{pmatrix} 0 & \mu_{12} & 0 & 0 \\ -\mu_{12} & 0 & 0 & 0 \\ 0 & 0 & 0 & \mu_{34} \\ 0 & 0 & -\mu_{34} & 0 \end{pmatrix} \otimes \mathbf{1}_3$$

- We find a CP-conserving solution with zero vacuum phase and each axion relaxing to zero one θ-angle
- The explicit mass operator appears
- The solution is directly related to the QCD one

The pNGB-axion dynamics

Axion mass matrix

Effective vacuum phases

$$\phi_{12} = -\frac{a_8 + a_{11}}{3f_a}\frac{\mu_{34}}{\mu_{34} - \mu_{12}}\ ,\ \phi_{34} = \frac{a_8 + a_{11}}{3f_a}\frac{\mu_{12}}{\mu_{34} - \mu_{12}}$$

- After substituting, we obtain the effective lagrangian for the axions
- Axions do not mix with neutral pNGB but η'_{TC}
- η'_{TC} decouples at the scale $\sqrt{a_t}$ higher than axion masses

Axion masses

$$\hat{a}_H = a_8\ ,\ m_H = \frac{\Lambda_8^2}{f_a} = 1\ \text{GeV} \cdot (\frac{\Lambda_8}{10^6\ \text{GeV}})^2 \frac{10^{12}\ \text{GeV}}{f_a} \qquad \hat{a}_L = \frac{1}{\sqrt{2}}(a_8 + a_{11})\ ,\ m_L^2 = \frac{4C_m f^3}{3f_a^2}\frac{\mu_{12}\mu_{34}}{\mu_{12} - \mu_{34}}$$

pNGB mass matrix

Masses from strong dynamics

Sector	Number of modes	m_π^2
μ_{12}-sector	14	$2B\mu_{12}$
μ_{34}-sector	14	$2B\mu_{34}$
μ_{12}–μ_{34} mixed sector	36	$B(\mu_{12} + \mu_{34})$
Relative diagonal mode	1	$B(\mu_{12} + \mu_{34})$

- The result is given in the degenerate Yukawa limit
- pNGB are lifted at the condensation scale

Masses from gauge boson loop

Spurion Classification	EW (R_2, Y)	Number of modes	m_π^2
μ_{12}-sector	(1, 0)	5	$2B\mu_{12}$
μ_{12}-sector	(3, 0)	3	$2B\mu_{12} + 2\kappa_g g^2 f^2$
μ_{34}-sector	(1, 0)	8	$2B\mu_{34}$
μ_{34}-sector	(1, ± 1)	3 + 3	$2B\mu_{34} + \kappa_g g'^2 f^2$
μ_{12}–μ_{34} mixed sector	(2, $\pm\frac{1}{2}$)	9 + 9	$B(\mu_{12} + \mu_{34}) + \frac{\kappa_g f^2}{4}(3g^2 + g'^2)$
Relative diagonal mode	(1, 0)	1	$B(\mu_{12} + \mu_{34})$

The pNGB dynamics and the Higgs boson

The Higgs as pNGB boson

pNGB EW doublets

- The breaking $SU(12) \to Sp(12)$ produces nine complex EW doublets pNGB (H^u_{ij}, H^d_{ij})
- They receive mass from $Sp(8)$ confinement scale, loops of gauge bosons and loop of Standard Model Quarks
- The loops of Standard Model quarks are induced by $Y\Psi\Sigma'\psi' + h.c.$ Operators
- The Higgs boson is the one coupled to the top quark, H^u_{33} and has a negative squared mass.
- Standard model quark loops communicate this choice to the remaining components of the doublets.

$$-\mu_b^2 H^u_{33} H^d_{33} - \mu_c^2 H^u_{33} (H^u_{22})^\dagger - \mu_{23}^2 H^u_{33} (H^u_{23} + H^u_{32})^\dagger + \text{h.c.}$$

Standard Model Flavour Structure

Partial Fundamental Compositness

- Standard Model Yukawas are generated by loops of technibarions

$$Y\Psi\underbrace{\Sigma'\psi'}_{\mathcal{B}} + h.c. \to \frac{YY'}{m^2_{\Sigma'}}\Psi\Psi\psi'\psi' \qquad \text{Heavy baryon}$$

- For top Yukawa a light baryon is needed $\approx \Lambda_{TC}$
- The baryon takes part to the strong dynamics and RGE effects can make the Yukawa coupling $\frac{YY'}{g_{TC}}$ of order one

Conclusions

- We solve the strong CP problem with two high quality axions in a composite Higgs scenario
- The high quality is obtained via the embedding of $SU(3)_c$ in $SU(11) \otimes Sp'(8)$
- The axions gets their mass from small instantons of $Sp'(8)$ and confinement scale of $Sp(8) \subset SU(11) \otimes Sp'(8)$
- Fermions in $Sp(8)$ condense and naturally give a state we identify with the Higgs Boson
- Standard Model flavour structure is naturally reproduced via Fundamental Partial Compositness
- The hierarchy problem is also addressed