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Strong CP Invariance in Higher Dimensions

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- Introduction
- Strong CP Problem
- Novel Approach
- Concrete Construction
  - Bulk color gauge theory
  - Boundary extra-quarks
  - Hypercolor and phenomenology
- Supersymmetric Extension
  - Supersymmetric setup
  - Supersymmetry breaking
  - Super-phenomenology
- Conclusion

- Standard Model
    - Cosmological constant
    - Strong CP
    - Gauge/Flavor Hierarchy
    - (Inflation)

SYMMETRY GEOMETRY

$$S_{QCD} = \int d^4x \; \frac{1}{2g_s^2} \mathrm{tr}(F_{\mu\nu}F^{\mu\nu})$$

$$+ \frac{\theta}{32\pi^2} \int d^4x \; \epsilon^{\mu\nu\rho\sigma} \mathrm{tr}(F_{\mu\nu}F_{\rho\sigma})$$

$$\theta_{eff} = \theta + \arg(\det Y)$$

$$\theta_{eff} = \langle a(x)/F_a \rangle$$

$$V(a) \simeq -\Lambda_{QCD}^4 \cos(a(x)/F_a)$$

Pecci-Quinn symmetry

$$\mathrm{U}(1)_{PQ} : a(x) \to a(x) + \xi F_a$$

Extra-Quarks

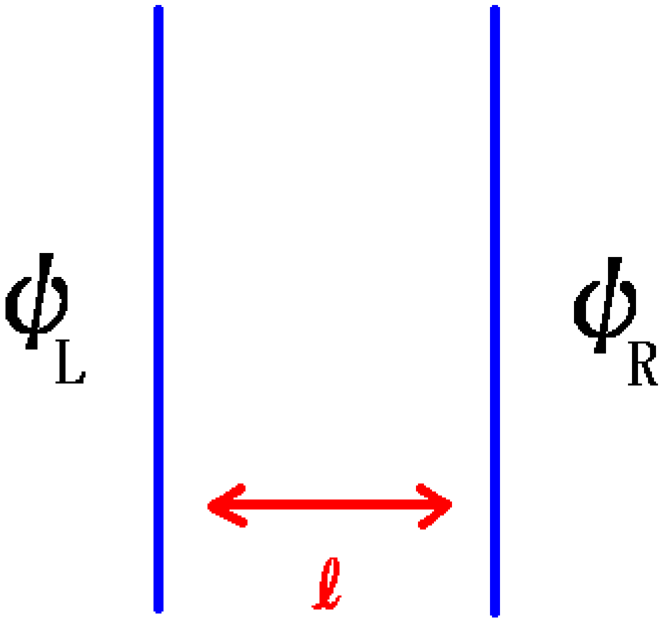
$$\psi_L \to e^{i\xi}\psi_L, \qquad \psi_R \to e^{-i\xi}\psi_R$$

Mass term

$$M_*\psi_L\psi_R^\dagger + \text{h.c.}$$

4-Fermi term

$$\frac{1}{M_*^2}(\psi_L\psi_R^\dagger)^2 + \text{h.c.}$$



$$\frac{M_* \psi_L \psi_R^\dagger}{e^{ml} - e^{-ml}}$$

$M_* \simeq 10^{18}$GeV: $ml \gtrsim 150$

local rigid symmetry   genericity

Effective Theory Descriptions

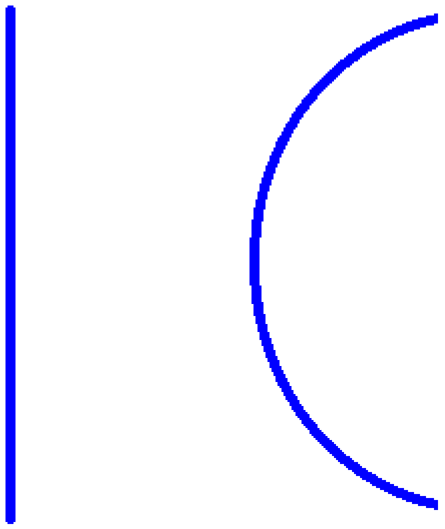
QCD	**Gravity**
strong CP	cosmological constant

changing to variable

chiral anomaly	spacetime inflation

selection by dynamics

axion	quintessence



$$g_{\mu\nu} = e^{2kl}\bar{g}_{\mu\nu}$$

$$R = e^{-2kl}\bar{R}\textbf{:} \quad kl \gtrsim 140$$

$$S_{YM} = \int d^4x \int_{-l}^{l} dy \; \frac{M_*}{4g^2} \mathrm{tr}(F_{MN}F^{MN})$$

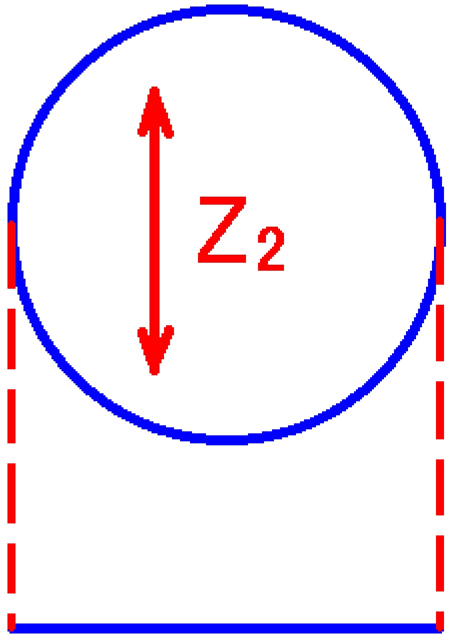
Parity symmetry

$$\mathbf{Z_2} : \begin{cases} A_\mu(x,y) \to A_\mu(x,-y) \\ \\ A_4(x,y) \to -A_4(x,-y) \end{cases}$$

Orbifolding

$$\begin{aligned} A_\mu(x,y) &= A_\mu(x,-y) \\ A_4(x,y) &= -A_4(x,-y) \end{aligned}$$

$$\varepsilon(x,y) = \varepsilon(x,-y)$$



$y = 0$ $y = \pm l$

Z_2-fixed planes

$$S_\psi = \int_{y=0} d^4x \ \bar{\psi}_L i \not{D} \psi_L + \int_{y=l} d^4x \ \bar{\psi}_R i \not{D} \psi_R$$

Gauge anomaly

$$\delta S_{eff} \ = \ \frac{i}{24\pi^2} \int_{y=0} \mathrm{tr} \left(\varepsilon d(AdA + \frac{1}{2} A^3) \right)$$

$$- \frac{i}{24\pi^2} \int_{y=l} \mathrm{tr} \left(\varepsilon d(AdA + \frac{1}{2} A^3) \right)$$

$$A = A_M dx^M$$

$$S_{CS} = \int h(y)\,\mathrm{tr}\left(AF^2 - \frac{1}{2}A^3F + \frac{1}{10}A^5\right)$$

$$F = dA + A^2$$

Parity symmetry: $h(y) = -h(-y)$

$$\begin{aligned}\delta S_{CS} &= \int h(y)\,\mathrm{tr}\left((d\varepsilon)d(AdA + \frac{1}{2}A^3)\right)\\ &= -\int (dh(y))\,\mathrm{tr}\left(\varepsilon d(AdA + \frac{1}{2}A^3)\right)\end{aligned}$$

$$S = S_{YM} + S_{CS} + S_{\psi}, \qquad \delta S = 0$$

$$h(y) = \frac{i}{48\pi^2}\frac{y}{|y|}$$

anomaly inflow

Color $\times$ Hypercolor: $\mathsf{SU(3)}_C \times \mathsf{SU(3)}_H$

$$\psi_L(\mathbf{3},\mathbf{3}^*), \qquad \psi_R(\mathbf{3},\mathbf{3}^*)$$

$$\left\langle \psi_L \psi_R^\dagger \right\rangle \simeq F_a^3 \qquad\qquad \mathbf{3}\times\mathbf{3}^* = \mathbf{8}+\mathbf{1}$$

$$\chi_L(\mathbf{1},\mathbf{3}^*), \qquad \chi_R(\mathbf{1},\mathbf{3}^*)$$

$$\left\langle \psi_L \psi_R^\dagger \right\rangle \simeq F_a^3, \qquad \left\langle \chi_L \chi_R^\dagger \right\rangle \simeq F_a^3$$

$$(\mathbf{3}+\mathbf{1})\times(\mathbf{3}^*+\mathbf{1}) = \mathbf{8}+\mathbf{3}+\mathbf{3}^*+\mathbf{1}+\mathbf{1}$$

$$\int_{y=0} d^4x \frac{1}{M_*^5} (\psi_L)^3 (\psi_L)^3$$
$$+ \int_{y=l} d^4x \frac{1}{M_*^5} (\psi_R^\dagger)^3 (\psi_R^\dagger)^3 + \text{h.c.}$$

$$\tilde{V}(a) \simeq \frac{F_a^{14}}{M_*^{10}} f(a/F_a)$$

$$\theta_{eff} \simeq \frac{F_a^{14}}{M_*^{10} {\Lambda_{QCD}}^4}$$

$M_* \simeq 10^{18}\mathrm{GeV}$, $\theta_{eff} < 10^{-9}$:

$F_a \lesssim 10^{12}\mathrm{GeV}$

- Supersymmetry

- Gravity

$(V, \Phi) \qquad \Phi \supset iA_4$

$$K = \frac{1}{4\pi}\,\mathrm{Im}\left(\frac{\partial \mathcal{F}(\Phi)}{\partial \Phi}\Phi^\dagger\right)$$

$$W = \frac{-i}{16\pi}\left(\frac{\partial^2 \mathcal{F}(\Phi)}{\partial \Phi^2}\right)\mathcal{W}^\alpha \mathcal{W}_\alpha$$

$$\mathcal{F} = i\tfrac{2\pi}{g^2}\Phi^2 + ih\Phi^3$$

$$\Rightarrow hA_4 F_{\mu\nu}F_{\rho\sigma}\epsilon^{\mu\nu\rho\sigma}$$

hep-th/9904096

by Y. Ohshima, K. Okuyama, H. Suzuki, and H. Yasuta

hep-th/0010288

by T. Kugo and K. Ohashi

M/CY$_3$

$C^{(3)} dC^{(3)} dC^{(3)}$ $\qquad$ $A = \int_{\mathcal{Q}_2} C^{(3)}$

Dp-brane

$$\int G_C d^{-1} \,\mathrm{tr}\left(\exp \frac{iF}{2\pi}\right)$$

Orbifolding

$$V(x,y) = V(x,-y)$$
$$\Phi(x,y) = -\Phi(x,-y)$$

Color $\times$ Hypercolor: $\mathrm{SU}(3)_C \times \mathrm{SU}(5)_H$

$Q = (Q^i{}_A, Q^4{}_A)$: $(\mathbf{3}+\mathbf{1}, \mathbf{5}^*)$

$\bar{Q} = (\bar{Q}_i{}^A, \bar{Q}_4{}^A)$: $(\mathbf{3}^*+\mathbf{1}, \mathbf{5})$

SU(5)$_H$ dynamics

$$W_{eff} = \frac{\Lambda_H^{11}}{\det Q_A \bar{Q}^A}$$

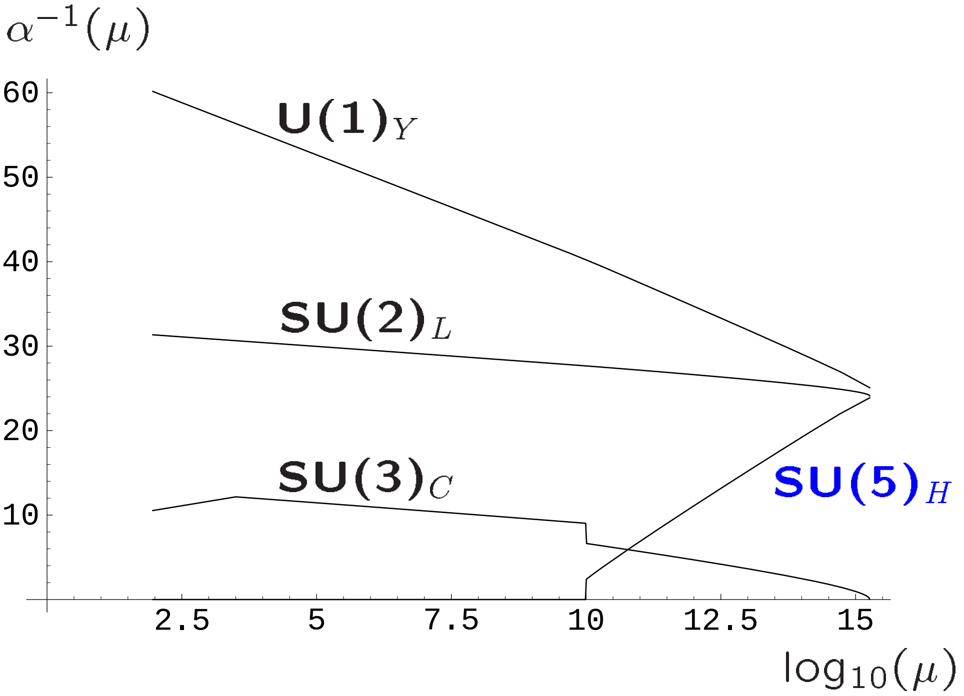
soft masses $V = m^2|Q|^2 + m^2|\bar{Q}|$

$$\left\langle Q_A \bar{Q}^A \right\rangle \sim \left(\frac{\Lambda_H^{11}}{m}\right)^{\frac{1}{5}}$$

$$(\mathbf{3}+\mathbf{1}) \times (\mathbf{3}^* + \mathbf{1}) = \mathbf{8} + \mathbf{3} + \mathbf{3}^* + \mathbf{1} + \mathbf{1}$$

$$\int_{y=0} d^4x d^2\theta d^2\bar{\theta} \frac{1}{M_*} Q^\dagger Q \bar{d}$$

$$\int_{y=0} d^4x d^2\theta d^2\bar{\theta} \frac{1}{M_*^4} (Q)^3 Q D^2 Q$$



$\alpha^{-1}(\mu)$
60
50
40
30
20
10
$\mathbf{U(1)}_Y$
$\mathbf{SU(2)}_L$
$\mathbf{SU(3)}_C$
$\mathbf{SU(5)}_H$
2.5
5
7.5
10
12.5
15
$\log_{10}(\mu)$

String/M Theory Realizations?

QCD | Gravity

strong CP | cosmological constant

background configurations

intersecting branes | flux vacua

objects inside

chiral fermions | anti-D branes