New Ideas on CPV

Matthew Schwartz
Johns Hopkins University

INT workshop on EDMs and CPV

March 20, 2007

Outline

- Strong CP: what is the problem?
- Old ideas on CPV
    - Axions
    - Spontaneous CPV
- New ideas on CPV
    - Strong CP as a flavor problem
    - New symmetries from extra dimensions
- Conclusions

Strong CP Simplified

The Simple Question:

The neutron has an EDM

$d_n = 10^{-16}$ e-cm θ) $\theta < 10^{-9}$

Why is θ so small?

The Simple Answer:

θ is just a parameter in the standard model Lagrangian.

Its renormalized value happens to be small

Matthew Schwartz
Johns Hopkins University

Strong CP Complicatified

Is there more to it?

- Other small parameters in the Standard Model Lagrangian are protected by symmetries

For example, $m_e = 10^{-6} \langle H \rangle$

protected by a chiral symmetry: $\psi_e \to e^{i\gamma_5 \alpha} \psi_e$

'**t Hooft naturalness**

So, quantum corrections to m_e are proportional to m_e

- No enhanced symmetry when $\theta = 0$

P and CP are already broken

However,

- If we set $\theta = 0$, quantum corrections are small

$$\Delta\theta \sim 10^{-18}$$

UV Sensitivity

What about UV sensitivity?

With a cutoff at M_{pl}:

$\Delta m_e / \quad m_e$ (tuning ~ 10^{-6}) } protected by 't Hooft naturalness UV finite

$\Delta m_h^2 / \quad M_{pl}^2$ (tuning ~ 10^{-34})

$\Delta \Lambda_{cc} / \quad M_{pl}^4$ (tuning ~ 10^{-120}) } UV sensitive

θ gets a logarithmically divergent correction at 7 loops

UV sensitive

$\Delta \theta \sim 10^{-18} + 10^{-30} \log (M_{pl}/m_q)$ (tuning ~ 10^{-10})

So, θ is *formally* UV sensitive, but

$\theta = 10^{-10}$ at M_{pl}) $\theta = 10^{-10}$ at 1 MeV

) θ is more like m_e than m_h

Strong CP is a flavor problem, not a naturalness problem

Axions

What are axions?

- Introduce complex scalar: $\Phi = \Phi_0 e^{ia}$
- New Peccei-Quinn Symmetry: $\left\{ \begin{array}{l} \Phi \to \Phi e^{i\delta} \quad (a \to a + \delta) \\ \theta \to \theta - \delta \end{array} \right.$ ← anomaly
- a dynamically relaxes $\theta = 0$

For example, two Higgs doublet model: $\mathcal{L} = Y_u Q_L \Phi u_R + Y_d Q_L \tilde{\Phi} d_R + \ldots$

However, PQ symmetry is anomalous

- nothing forbids $\mathcal{L} \to \mathcal{L} + g_5 M_{pl}^{-1} \Phi^4(\Phi + \Phi^*) + g_1 M_{pl}^3 (\Phi + \Phi^*)$

  $g_5 < 10^{-54}$ $\qquad$ $g_1 < 10^{-189}$

- reintroduces UV sensitivity

  $\theta = 0$ at M_{pl}) $\qquad$ $\theta \sim 1$ at 1 MeV

- Axions treat strong CP as a naturalness problem, but make the problem worse!
- Axions teach us nothing about flavor

Matthew Schwartz
Johns Hopkins University

Massless up quark

What about the m_u=0 solution?

- There is no enhanced symmetry at $m_u = 0$

Neutron EDM is

$$d_n = 10^{-16}\,\text{e-cm}\left(\frac{m_u}{1\ \text{MeV}}\right)\theta$$

) m_u< 1 eV = 10^{-15} h H i

- More natural just to set $\theta = 10^{-10}$!
- Ruled out: m_u ~ 1 MeV
- Even if it did work, setting m_u=0 teaches us nothing about flavor

Matthew Schwartz
Johns Hopkins University

Strong CP and flavor

Why else is strong CP like a flavor problem?

There are two θ angles:

$\mathcal{L} = \ldots + \theta_{QCD} F \tilde{F}$

θ_{flavor} = Arg Det [Y_u Y_d]

The observable is $\theta = \theta_{QCD} + \theta_{flavor} < 10^{-9}$

There is another CP violating phase

$$\theta_{weak} = \text{Arg Det} [Y_u Y_d - Y_d Y_u] \sim 1$$

If θ_{QCD} =0, the Strong CP problem is exactly a flavor problem:

Why are **some** yukawa couplings smaller than **others**?

Spontaneous CPV

- Suppose CP is a good symmetry at high energy

$$\theta_{QCD} = \theta_{flavor} = \theta_{weak} = 0$$

- CP is spontaneously broken

$$\text{CP}: \Phi \rightarrow -\Phi$$

$$\langle \Phi \rangle \neq 0$$

- Try to arrange

$$\theta_{weak} = \text{Arg Det } [Y_u\, Y_d - Y_d\, Y_u] \sim 1$$

$$\theta_{flavor} = \text{Arg Det } [Y_u\, Y_d] < 10^{-10}$$

$$\theta_{QCD} < 10^{-10}$$

- Examples
  - Nelson-Barr models
  - Extra dimensional models: Twisted Split Fermions
  - Left-Right symmetric models

Matthew Schwartz
Johns Hopkins University

Nelson-Barr

Phys.Lett.B136:387,1984
Phys.Rev.Lett.53:329,1984

- renormalizable theory
- field content:
  - standard model: Q_L, H, u_R, d_R
  - **CP** violating scalar: Φ
  - heavy vectorlike generators: **R**
- new global symmetries
- achieves $\theta = 0$ and $\theta_{weak} \sim 1$ classically
- to maintain small θ in quantum theory requires

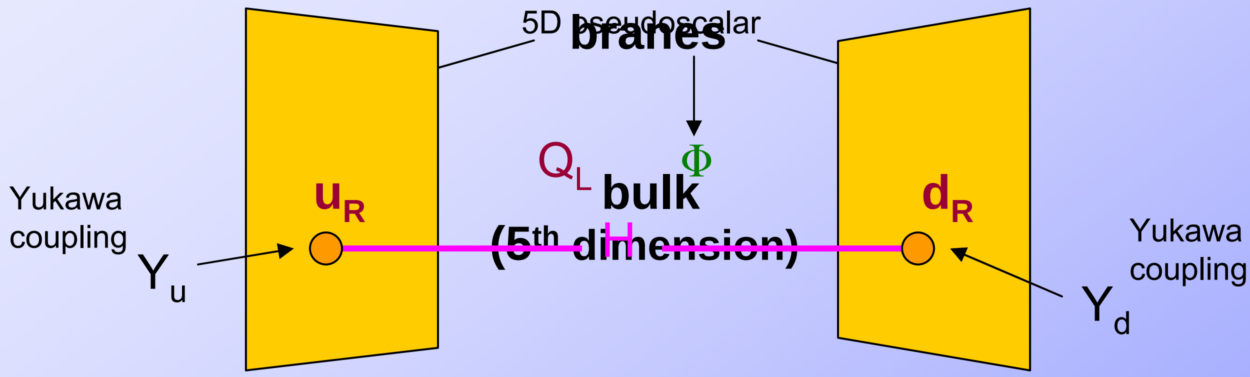
$$\Lambda \gg \langle \Phi \rangle \gg M_{RR} \gg \langle H \rangle$$

tuning ~ 10^{-5} (for $\Lambda \gg \langle \Phi \rangle$)

technically natural (for $\langle \Phi \rangle \gg M_{RR}$)

ordinary hierarchy problem (for $M_{RR} \gg \langle H \rangle$)

Extra Dimensions



$$L = m_{ij}\,\copyright\,\bar{Q}Q + m^{y}_{ij}\,\copyright^{?}\,\bar{Q}Q + ¢¢¢$$

Impose CP: $Q(z) \to \bar{Q}(z)$, $\Phi(z) \to \Phi^{*}(z)$) { Yukawas Y_u and Y_d are real; $\theta = 0$, $\theta_{weak} = 0$

Φ gets a complex vev

- **CP** is spontaneously broken
- Q_L gets a mass

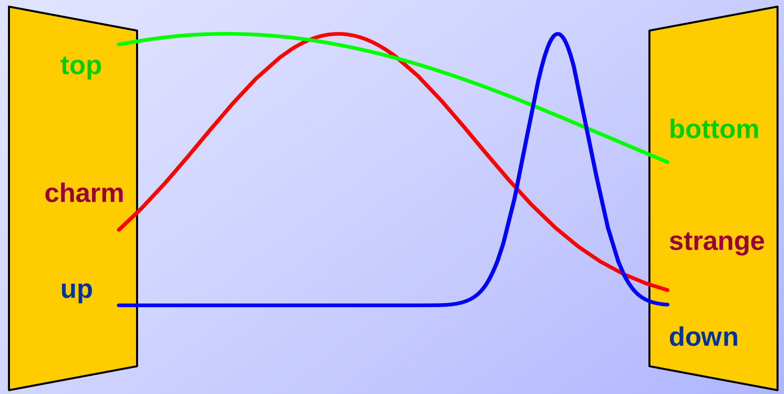
automatically Hermetian

$$M_{ij} = m_{ij}\,h\copyright i + m^{y}_{ij}\,h\copyright^{?} i$$

Matthew Schwartz
Johns Hopkins University

Twisted Split Fermions

Dirac equation $\partial_z Q_i = M_{ij} Q_j$ leads to exponential profiles



split fermions

hep-ph/9903417

twisting

$$Q_i(z) = e^{\int M_{ij}(z)dz} Q_j(0) = K_{ij}(z) Q_j(0)$$

complex **hermetian** matrix

product of hermetian matrices
complex, with **real determinant**

hep-ph/0407260
hep-ph/0411132

effective Yukawa matrices are $Y_u^{eff} = Y_u$ and $Y_d^{eff} = K(L)\, Y_d$, so

$$\theta = \text{ArgDet}(Y_u K Y_d) = 0$$

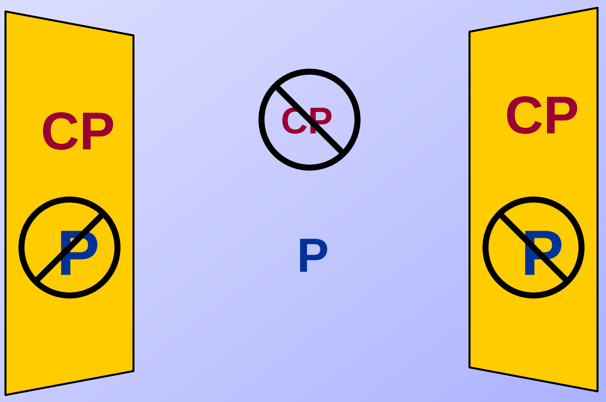
$$\theta_{weak} = \text{ArgDet}(Y_u K Y_d - K Y_d Y_u) \sim 1$$

Matthew Schwartz
Johns Hopkins University

What happened?

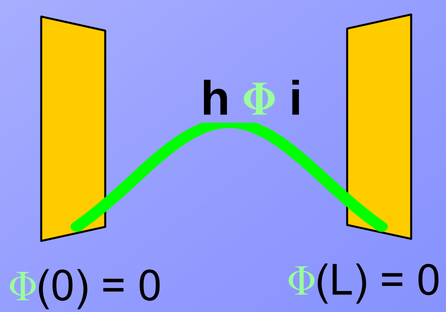
θ violates both **P** and **CP**

but either **P** and **CP** is protected everywhere



P is part of 5D Lorentz invariance

- bulk mass M_{ij} must be Hermetian
- source of **CPV**, Φ, is a 5D psuedoscalar



Matthew Schwartz
Johns Hopkins University

How big is θ in twisted split fermions?

• After spontaneous symmetry breaking, h Φ i≠ 0

$$\theta_{QCD} = \theta_{flavor} = 0 \qquad\qquad \theta_{weak} \sim 1$$

• estimate quantum corrections by adding ***all*** operators consistent with symmetries

bulk operators can never contribute to θ by **P**

Φ FF (crossed out)

boundry operators can never contribute to θ by **CP** ($\Phi(0) = \Phi(L) = 0$)

Φ FF$\delta(z)$ (crossed out)

• leading operator is

$$\frac{p\ \overline{24¼^3}}{¤^{7=2}} (d_z\Phi - d_z\Phi^*)\, FF\delta(z) \quad) \qquad \theta \sim 10^{-7}$$

• if $\Phi = \Phi_{ab}$ is a flavor adjoint

$$\frac{24¼^3}{¤^6} (d_z\Phi)^2\, FF\delta(z) \quad) \qquad \theta \sim 10^{-12}$$

NDA $\left\{ \begin{array}{l} ¤ = \frac{24¼^3}{g_s^2 L} \\ \text{h } \Phi \text{ i} = 1/L \end{array} \right.$

Left-right symmetric models

hep-ph/9707281

- renormalizable
- use right-handed doublets: Q_L, Q_R, Φ
- use **P,** instead of **CP,** to set θ=0 classically
- effective mass matrix is

$$M_{ij} = (f_{ij} + f_{ij}^{\dagger})\langle\Phi\rangle$$

must have real determinant for θ=0

1. Impose **CP**

   f_{ij} is real

   $\langle\Phi\rangle$ is complex

   } $\det(M_{ij})$ is complex

2. no **CP**

   f_{ij} is complex

   $\langle\Phi\rangle$ is real

   } $\det(M_{ij})$ is real

why?

real determinant guaranteed by 5D lorentz invariance

Twisted Split Fermions have $M_{ij} = m_{ij}\langle\Phi\rangle + m_{ij}^{\dagger}\langle\Phi^{*}\rangle$

Matthew Schwartz
Johns Hopkins University

Other ideas

Axions

- String axions
  - Can calculate (in principle) whether there is explicit PQ violation
  - Difficult to get $f_a \sim 10^{-12}$ GeV
- Warped axions (hep-ph/0611278)
  - Use Randall-Sundrum like warping to generate $f_a \sim 10^{-12}$ GeV
  - Without an explicit string construction, still unnatural
- Three-form axions (hep-th/0507215)
- Gauged axions (hep-ph/0103346)
  - Anomaly canceled by sequestered fermions in an extra dimension
  - Seems promising, but no explicit models have been constructed

Spontaneous CPV

- Hiller-Schmaltz (hep-ph/0212151)
  - Use supersymmetry to keep $\theta = 0$, but allow $\theta_{weak} \sim 1$
- Warped-twisting
  - Twisted split fermions in Randall-Sundrum context
  - May have complimentary insights into flavor

Conclusions

- The Strong CP problem is easy to solve

$$\theta_{ren} = 10^{-10}$$

- If you think this solution is unnatural, you must have a more natural solution
  - Axions are less natural
  - $m_u = 0$ is less natural
  - Left-Right models are less natural
- Instead, we can think of θ as a flavor parameter
  - "why is $\theta = 10^{-10}$?" like "why is $m_{electron} = 10^{-6}\, m_{top}$?"
- Spontaneous **CPV** explains why QCD vacuum angle $\theta_{QCD} = 0$
- Extra dimensions are a natural flavor framework
  - Split fermions explain mass hierarchies
  - Twisting explains weak CP phase
  - 5D Lorentz invariance (partity) and 5D locality protect θ
- In Twisted Split Fermions, expect

$$\theta \sim 10^{-12}$$

Matthew Schwartz
Johns Hopkins University