Super-Soft CP violation

Alessandro Valenti

Department of Physics and Astronomy "Galileo Galilei" - University of Padova

SUSY 2021 - 27 August 2021

Based on the works:
[1] L. Vecchi, AV "The CKM Phase and $\bar{\theta}$ in Nelson-Barr Models" JHEP07(2021)203
[2] L. Vecchi, AV "Super-Soft CP Violation" JHEP07(2021)152

The Strong CP problem

$$\mathcal{L}_{topo}^{QCD} = \frac{g_s^2}{32\pi^2}\bar{\theta}\, G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}, \qquad \bar{\theta} = \theta_{QCD} + \arg\det Y_u Y_d \lesssim 10^{-10}$$ C. Abel et al. (2020)

Solutions? Spurious symmetries of $\mathcal{L}_{topo}^{QCD}$:

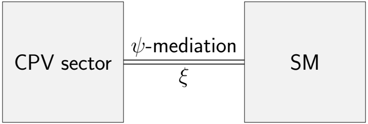
- anomalous $U(1)$: $\bar{\theta} \to \bar{\theta} + \alpha$
  - -) linear: massless up quark $\to$ ruled out (PhysRevLett.125.232001 (2020))
  - -) non-linear: $U(1)_{PQ} \to$ axion
- P: $\bar{\theta} \to -\bar{\theta}$. Mirror world, ...
- CP: $\bar{\theta} \to -\bar{\theta}$. **Nelson-Barr models**

} "good" UV symmetries: gauged in extra dimensions

Dine, Leigh, MacIntire (1992)

Choi, Kaplan, Nelson (1993)

Nelson-Barr models



Focus on "*d*-mediation"

(q excluded, u fine-tuned. See [1] and L. Vecchi, JHEP04(2017)149)

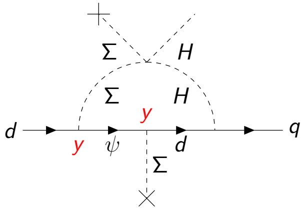
$$-\mathcal{L}^{d}_{\text{Yuk}} = y_u qHu + y_d q\widetilde{H}d + y\Sigma\psi d + m_\psi \psi\psi^c + hc$$

- UV: CP is a symmetry. $y_d, y_u, y_\ell, y, m_\psi \in \mathbb{R}$ & $\theta_{QCD} = 0$
- IR: $\Sigma \to \langle\Sigma\rangle \in \mathbb{C}$. Spontaneous CPV, controlled by $\xi^\dagger = y\langle\Sigma\rangle$. Nelson-Barr class: $\bar{\theta}_{tree} = 0$. But
  1) can we keep $\bar{\theta} < 10^{-10}$, including loop and UV effects?
  2) can we reproduce SM CPV?

Complete study in [1]. In summary:

1) a) $\Sigma^\dagger \Sigma G \widetilde{G} / f_{UV}^2 < 10^{-10} \longrightarrow \langle \Sigma \rangle / f_{UV} < 10^{-5}$. CP violation must be soft

b) "reducible" contributions:
need $y \ll 10^{-3} - 10^{-4}$



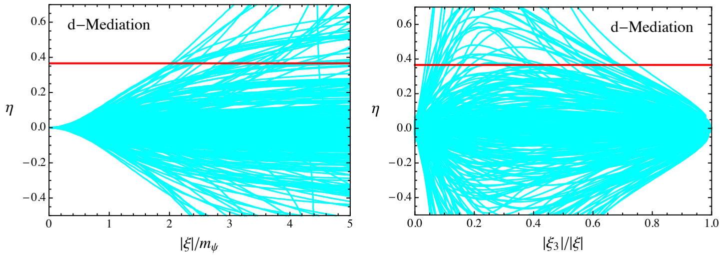
c) "irreducible" contributions of ψ + SM:

-) decoupling 2-loops ok for $M \gtrsim$ TeV $(M^2 = \xi^\dagger \xi + m_\psi^2)$
-) non-decoupling 3-loops: ok, only weak bounds on ξ / m_ψ (stronger from 2) later)

d) must avoid $q\tilde{H}\psi^c$: chiral $U(1)$ needed
(non-decoupling 2-loops too big)

2) Diagonalizing, $Y_d Y_d^\dagger = y_d \left(1 - \frac{\xi\xi^\dagger}{M^2}\right) y_d^T$. Reproduces SM if

$$1 < \frac{|\xi|}{m_\psi} \ll 10^3$$



[1] L. Vecchi, AV. JHEP07(2021)203

How can we guarantee 1), 2) from a UV point of view?

Idea

Confining CPV sector with chiral $U(1)$:

$$y\psi\Sigma d \to \frac{\chi\chi^c\psi d}{f_{UV}^2} \qquad\qquad m_\psi\psi\psi^c \to \frac{\lambda\lambda\psi\psi^c}{f_{UV}^2}$$

$$\frac{\langle\chi\chi^c\rangle}{f_{UV}^2} \sim \frac{\langle\lambda\lambda\rangle}{f_{UV}^2} \sim \frac{4\pi f^3}{f_{UV}^2} \Longleftrightarrow y\langle\Sigma\rangle \sim m_\psi \text{ 2)}$$

- Selection rules: only non-renormalizable operators 1a), no $q\tilde{H}\psi^c$ 1c)
- $f/f_{UV} < 10^{-5}$ by dimensional transmutation 1a)
- $y \sim 4\pi f^2/f_{UV}^2 \ll 10^{-4}$ 1b)

How does CPV arise?

Spontaneous CP violation

Vafa-Witten:

$$\langle \chi_\alpha \chi^c_\beta \rangle = C\delta_{\alpha\beta}, C = C^\dagger.$$

CPV only from higher-dimensional operators generating potential for pNGBs:

$$\mathcal{L}_{UV} \supset c_{\alpha\beta;\gamma\delta} \frac{(\chi_\alpha \chi^c_\beta)(\chi_\gamma \chi^c_\delta)^\dagger}{f^2_{UV}}$$

$$\langle \chi\chi^c \rangle \sim 4\pi f^3 e^{i\langle\pi\rangle/f} \to \text{CPV!} \qquad (m_\pi \sim 4\pi \frac{f^2}{f_{UV}})$$

- but how to keep m_ψ real? $\to$ gauge the chiral U(1)

  ·) pNGB of $\lambda\lambda$ eaten by A_μ: no physical m_ψ phase ($m_A \sim gf$)
  ·) possible hadrons phases $\to$ need $f/f_{UV} < 10^{-5}$

Within this framework the Strong CP problem is robustly solved

- $m_\psi \ll 4\pi f \ll 4\pi f_{UV}$: CP violation is *Super-soft*

  pNGBs and hadrons interactions irrelevant: $\sim f^2/f_{UV}^2$ suppression
  Additional unrelated NP allowed as long as $\Lambda_{NP} \gg m_\psi$.

Within this framework the Strong CP problem is robustly solved

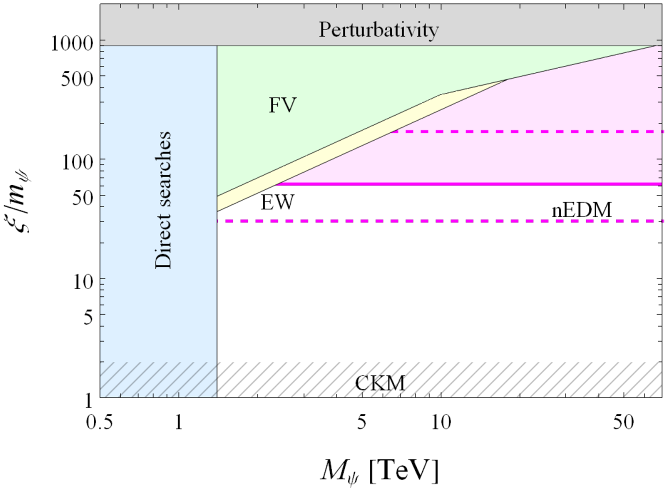
- $m_\psi \ll 4\pi f \ll 4\pi f_{UV}$: CP violation is *Super-soft*

  pNGBs and hadrons interactions irrelevant: $\sim f^2/f_{UV}^2$ suppression
  Additional unrelated NP allowed as long as $\Lambda_{NP} \gg m_\psi$.

- Predictivity: taking $f_{UV} \sim M_P$, $m_\psi \sim 4\pi \frac{f^3}{M_P^2} \sim 10^{-14}\, M_P \sim$ 10's TeV

  Directly (collider) and indirectly (flavor & CP observables) accessible!

Within this framework the Strong CP problem is robustly solved



[1] L. Vecchi, AV. JHEP07(2021)203

Within this framework the Strong CP problem is robustly solved

- $m_\psi \ll 4\pi f \ll 4\pi f_{UV}$: CP violation is *Super-soft*

  pNGBs and hadrons interactions irrelevant: $\sim f^2/f_{UV}^2$ suppression
  Additional unrelated NP allowed as long as $\Lambda_{NP} \gg m_\psi$.

- Predictivity: taking $f_{UV} \sim M_P$, $m_\psi \sim 4\pi \frac{f^3}{M_P^2} \sim 10^{-14}\, M_P \sim$ 10's TeV

  Directly (collider) and indirectly (flavor & CP observables) accessible!

- Extra states: confining sector generically requires other (almost) decoupled states → DM & cosmological signatures

Within this framework the Strong CP problem is robustly solved

- $m_\psi \ll 4\pi f \ll 4\pi f_{UV}$: CP violation is *Super-soft*

  pNGBs and hadrons interactions irrelevant: $\sim f^2/f_{UV}^2$ suppression
  Additional unrelated NP allowed as long as $\Lambda_{NP} \gg m_\psi$.

- Predictivity: taking $f_{UV} \sim M_P$, $m_\psi \sim 4\pi \frac{f^3}{M_P^2} \sim 10^{-14}\, M_P \sim$ 10's TeV

  Directly (collider) and indirectly (flavor & CP observables) accessible!

- Extra states: confining sector generically requires other (almost) decoupled states $\rightarrow$ DM & cosmological signatures

- Baryogenesis: possible through low scale leptogenesis

Conclusion

Robust solutions of the Strong CP problem based on Spontaneous CP violation can be built. In the UV, CP is *exact*: no quality problem

A confining CP violating sector works well and is remarkably predictive: VLQ at collider scale and possible cosmological signatures

SUSY-based completions can address some of the issues, but leave questions (why m_ψ real?)

Thanks for your attention!

Requirements for a real m_ψ:

i) λ must appear in a single family (no chiral flavor symmetries for λ)

ii) the chiral $U(1)$ must be gauged

iii) the chiral $U(1)$ must commute with the flavor symmetries of χ, χ^c

iv) $f/f_{UV} < 10^{-5}$

In this way:

- $i) - iii)$: the unique pNGB $\lambda\lambda \sim 4\pi f^3 e^{i\rho}$ of the axial $U(1)$ is eaten by A_μ, no physical phase

- $iv)$: other sources for $\langle\lambda\lambda\rangle$'s phase
  - contamination from other pNGB, at least dim. 6+ operators
  - composite hadrons at $\sim 4\pi f$ with $V = V_0 + V_1$. V_0 conserves CP (Vafa-Witten), V_1 dim.6+ $\to \arg m_\psi \sim V_1/V_0 \sim f^2/f_{UV}^2$

Taking $f/f_{UV} < 10^{-5}$ addresses both.

An explicit realization

Fields	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$	$SU(3)$	$U(1)$
ψ_1	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$	$\mathbf{1}$	$+1$
ψ_2	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$	$\mathbf{1}$	-1
ψ_1^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$+\frac{1}{3}$	$\mathbf{1}$	$-\frac{1}{3}$
ψ_2^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$+\frac{1}{3}$	$\mathbf{1}$	$+\frac{1}{3}$
ψ_1'	$\mathbf{1}$	$\mathbf{2}$	$+\frac{1}{2}$	$\mathbf{1}$	$+1$
ψ_2'	$\mathbf{1}$	$\mathbf{2}$	$+\frac{1}{2}$	$\mathbf{1}$	-1
$\psi_1'^c$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	$\mathbf{1}$	$-\frac{1}{3}$
$\psi_2'^c$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	$\mathbf{1}$	$+\frac{1}{3}$
$\chi_{\alpha=1,2}$	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{3}$	$+\frac{1}{2}$
$\chi_{\alpha=1,2}^c$	$\mathbf{1}$	$\mathbf{1}$	0	$\overline{\mathbf{3}}$	$+\frac{1}{2}$
λ	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{8}$	$-\frac{1}{3}$
$N_{I=1,2,3,4}$	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$-\frac{2}{3}$
$N'_{I=1,2,3,4}$	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}$	$-\frac{1}{6}$

Interactions:

- CPV mediation: $\langle \chi_\alpha \chi_\beta^c \rangle = c_\chi 4\pi f^3 \left(e^{i\frac{\pi\cdot\sigma}{f}}\right)_{\alpha\beta}$,

$$(\chi_\alpha \chi_\beta^c)^\dagger \psi_1 d, \quad \chi_\alpha \chi_\beta^c \psi_2 d, \quad (\chi_\alpha \chi_\beta^c)^\dagger \psi_1' \ell, \quad \chi_\alpha \chi_\beta^c \psi_2' \ell$$

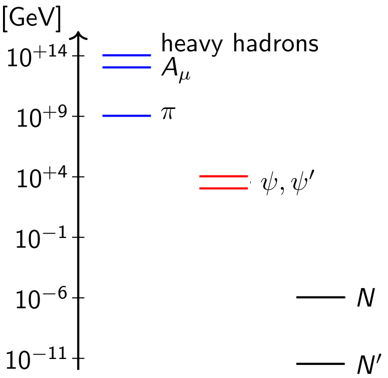
- m_ψ: $\langle \lambda\lambda \rangle = c_\lambda 4\pi f^3$,

$$\psi_1 \psi_1^c \lambda\lambda, \quad \psi_2 \psi_2^c (\lambda\lambda)^\dagger, \quad \psi_1' \psi_1'^c \lambda\lambda, \quad \psi_2' \psi_2'^c (\lambda\lambda)^\dagger$$

- CPV potential: $c_{\alpha\beta;\gamma\delta}(\chi_\alpha \chi_\beta^c)(\chi_\gamma \chi_\delta^c)^\dagger / f_{UV}^2$.
  $m_\pi \sim 4\pi f^2 / f_{UV} \sim 10^{8-9}$ GeV

- Spectator masses:
  -) $\chi_\alpha \chi_\beta^c \lambda N_I / f_{UV}^2$. Seesaw with $\langle \chi \chi^c \lambda \rangle$, $m_N \sim 4\pi f^5 / f_{UV}^4 \sim$ KeV
  -) $N' N' (\chi\chi^c)(\lambda\lambda)/f_{UV}^4$. $m_{N'} \sim 4\pi f^6 / f_{UV}^5 \sim$ meV

- Other irrelevant dim. 6 interactions, suppressed by f_{UV}^2.



- ψ, ψ' phenomenology: see [1]. Indirect observables (FV): large portion of parameters space allowed. Direct search @LHC: $m_\psi > 1.4$ TeV
- Cosmology: need $T_{REH} \ll 4\pi f/25 \sim 10^{11-13}$ GeV to avoid defects. N warm DM:

$$\frac{\rho_N}{s} \simeq \frac{\rho\ \mathrm{DM}}{s} \left(\frac{\sum_{I=1}^{4} m_{N_I}}{4\ \mathrm{keV}}\right) \left(\frac{10^{13}\ \mathrm{GeV}}{f}\right)^4 \left(\frac{T_{REH}}{10^{11}\ \mathrm{GeV}}\right)^3$$

Baryogenesis: modify spectator sector

	$U(1)$
$N_{1,2}$	$-\frac{1}{3}$
$N'_{1,\cdots,5}$	$-\frac{2}{3}$
$X_{1,2,3}$	$+\frac{1}{2}$
$X'_{1,\cdots,5}$	$-\frac{1}{6}$

- Interactions: $\psi_2'^c HN$ and dim.6 Majorana masses for N, N', X, dim.9 for X'
- Baryogenesis through resonant leptogenesis via $N, N' \to {\psi'^c}^\dagger H^\dagger, \psi'^c H \to \ell^\dagger H^\dagger, \ell H$
- $m_X \sim$ TeV: cold DM candidate for $T_{REH} \sim 10^8$ GeV