The Nelson-Barr Axion Dark Matter

(converting the LHC+B-factories into quantum sensors)

Gilad Perez

Weizmann

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Outline

- Intro. the strong CP problem + ultralight dark-matter
- The Nelson-Barr solution to the strong CP problem
- The strong-CP axion
- New pheno’ new signatures for the LHC+B-factories
- Challenges of the model

How serious is the strong CP problem ?

- 3 levels of formulating the strong CP problem:

(*i*) $\bar{\theta} = \theta - \arg\left[\det\left(Y_u Y_d\right)\right] \lesssim 10^{-10}$, is it a problem?

(who knows?)

(*ii*) $\bar{\theta} = \lesssim 10^{-10} \ll \theta_{\mathrm{KM}} = \arg\left\{\det\left[Y_u Y_u^\dagger, Y_d Y_d^\dagger\right]\right\} = \mathcal{O}(1)$, is it a problem?

(not if these are natural/protected and sequestered)

(*iii*) $\bar{\theta} = \lesssim 10^{-10} \ll \theta_{\mathrm{KM}}$, but $\bar{\theta} = \bar{\theta}_{\mathrm{bare}} + \epsilon\,\theta_{\mathrm{KM}} \ln\left(\Lambda_{\mathrm{UV}}/M_W\right)$, is it a problem?

(ϵ appears in 7 loops and contains several other suppression factor)

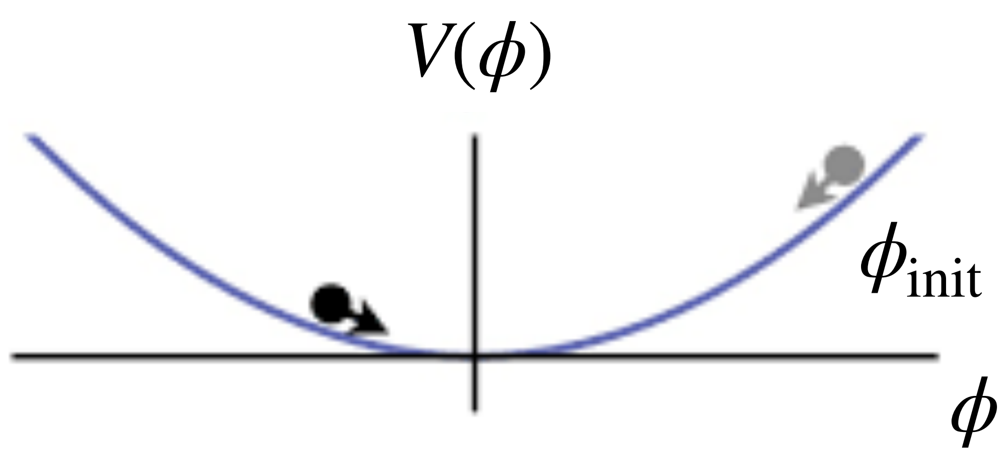
- Should we be cautious [at least till we reach $\mathcal{O}\left(10^{-16}\right)$ precision]

We nevertheless focus on axions

- Begin with ultralight dark matter (UDM), minimal model would be just a free massive scalar:

$$\mathscr{L} \in m_\phi^2 \phi^2 \,, \; \rho_{\rm Eq}^{\rm DM} \sim {\rm eV}^4 \sim m_\phi^2 \phi_{\rm Eq}^2 = m_\phi^2 \phi_{\rm init}^2 ({\rm eV}/T_{\rm osc})^3 \qquad \left[T_{\rm os} \sim \sqrt{M_{\rm Pl} m_\phi}\right]$$

minimal misalignment mechanism



- Assuming ("best case") MeV reheating: $$\phi_{\rm init}\,(f_{\rm min}) = \begin{cases} 10^{17}\,{\rm GeV}\left(\frac{10^{-27}\,{\rm eV}}{m_\phi}\right)^{\frac{1}{4}} & m_\phi \lesssim 10^{-15}\,{\rm eV} \\ 10^{15}\,{\rm GeV}\left(\frac{10^{-15}\,{\rm eV}}{m_\phi}\right) & m_\phi \gtrsim 10^{-15}\,{\rm eV} \end{cases}$$

Solving the QCD problem ***not*** with QCD axion

- There's a class of models where CP is UV-sym' and at tree level we find:

$$\bar{\theta} = \theta - \arg\left[\det\left(Y_u Y_d\right)\right] = 0 \quad \& \quad \theta_{\rm KM} = \arg\left\{ \det\left[Y_u Y_u^\dagger, Y_d Y_d^\dagger\right]\right\} = \mathcal{O}(1)$$

- This is realized if:

1. Yukawas are Hermitian (left-right models or wave function renorm')

Hiller & Schmaltz (01); Harnik, GP, Schwartz & Shirman (04); Cheung, Fitzpatrick & Randall (08)

2. Structure/sym. => det(0), concretely, Nelson-Barr (NB) Nelson; Barr (84)

- We focus on NB, which are easy to control & of higher quality

Nelson-Barr (crash course)

- $\mathscr{L}_{\rm NB} = \mu q^c q + (g_i \Phi + \tilde{g}_i \Phi^*) d_i^c q + Y_d H Q d^c + Y_u \tilde{H} Q u^c \quad \left(\text{with } \; q, q^c, \Phi \subset \; Z_2 - \text{odd}\right)$

- Assume that theory is real and only $\Phi = \frac{f+\rho}{\sqrt{2}} \exp\left(\frac{ia}{f}\right)$; $\langle a \rangle \neq 0$ breaks CP, then:

1. $\mathscr{M}_d = \begin{pmatrix} \mu & B_i \\ 0 & m_d \end{pmatrix}$; $m_d \equiv Y_d v$; $B_i \equiv (g_i \Phi + \tilde{g}_i \Phi^*)$ => det $\left[\mathscr{M}_d\right] \in$ Real

2. At low energy ($v \ll \mu, g_i f$), effective m_d satisfies $m_d^{\rm eff} m_d^{\rm eff \dagger} = m_d \left(\mathbf{1}_3 + \frac{B_i^* B_j}{\mu^2 + B_f B_f^\dagger} \right) m_d^\dagger$,

   which if g_i isn't parallel to $\tilde{g}_i$ and $\mu \lesssim B_i$ lead to $\theta_{\rm KM} = \mathcal{O}(1)$

Nelson-Barr axion-like pheno for the CP breaking

Discussion with: M. Dine, Y. Nir, W. Ratzinger, I. Savoray

- $\mathscr{L}_{\rm NB} = \mu q^c q + (g_i\Phi + \tilde{g}_i\Phi^*)d_i^c q + Y_d HQd^c + Y_u\tilde{H}Qu^c \quad \left(\text{with } q, q^c, \Phi \subset Z_2 - \text{odd}\right)$

- Assume approx' flavor sym' such that $g_i \propto (1,0,0) \quad \& \quad \tilde{g}_i \propto (0,0,1)$

- Then a is a pseudo-Nambu-Goldstone-boson, with suppressed potential, but with $\langle a \rangle = 0$

- Furthermore, one can show that $\theta_{\rm KM} = \dfrac{a}{f}$

Involved the 3rd generation

$$\left\{ m_d^{\rm eff} m_d^{\rm eff\dagger} \sim m_d \left[\mathbf{1}_3 + r \begin{pmatrix} 1 & 0 & e^{\frac{2ia}{f}} \\ 0 & 0 & 0 \\ e^{\frac{-2ia}{f}} & 0 & 1 \end{pmatrix} \right] m_d^T \right\}$$

- Also, mixing angles develop quadratic dependence on a (but not masses)

Nelson-Barr ultralight-DM pheno

With: M. Dine, Y. Nir, W. Ratzinger, I. Savoray (also discussion with Surjeet)

- In case another sector breaks the shift sym' (say Planck suppress or other) then the minimum of potential generically would lead to $\langle a \rangle \neq 0$ and spontaneous breaking of CP => $\bar{\theta} = 0$ & $\theta_{\mathrm{KM}} = \mathcal{O}(1)$

Relaxion: Graham, Kaplan & Rajendran (15)

NB-relaxion - Davidi, Gupta, GP, Redigolo, & Shalit (17)

- Now if we tip the NB-axion from it's minimum it'd behave as a new type of ultralight DM

↓

New type of pheno: *time dependent CKM angles*

While the strong CP is always zero

NB-UDM signature & parameter space

- What is the size of the effect? $\delta\theta_{\rm KM} \sim \frac{\sqrt{\rho_{\rm DM}}}{m_{\rm NB} f}\cos(m_{\rm NB}t) \sim 10^{-3} \times \frac{10^{10}\,{\rm GeV}}{f} \times \frac{10^{-19}\,{\rm eV}}{m_{\rm NB}} \times \cos(m_{\rm NB}t)$

- Currently (PDG): $\theta_{\rm KM} = 1.14 \pm 0.03$

- How to search such signal? Need time dependence CP violation, perfect for B-asym

- Bound from EP: $\frac{\Delta m_u}{m_u} \approx \frac{3}{32\pi^2} y_b^2 |V_{ub}^{\rm SM}|^2 \frac{a}{f} \Rightarrow f \gtrsim 10^{10}\,{\rm GeV}$

- Minimal misalignment DM bound, can't be satisfied: $f \gtrsim 10^{15}\,{\rm GeV}\left(\frac{10^{-19}\,{\rm eV}}{m_\phi}\right)^{\frac{1}{4}}$

- Naive naturalness => sub-MeV cutoff , $\Delta m_a \approx \frac{y_b |V_{ub}| m_u \Lambda_{\rm UV}}{16\pi^2 f}$ => current B-factories probe finely tuned region

Conclusions

- The strong CP problem is marginally a problem but it is interesting to try and solve it
- Nelson-Barr models account for the smallness of the strong CP phase & the fact the KM phase is order one, which requires spontaneous CP violation
- Spontaneous breaking lead to the presence of a light axion-like field
- If this field consist of ultralight dark matter it'd lead to new type of pheno', with time-dependent CKM angles (involving the 3rd gen')
- Maybe be probed by the LHC/B-factories