The R-xion: Protecting the Peccei-Quinn Symmetry by means of Non-Anomalous Discrete R Symmetries.

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Outline

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The Peccei-Quinn Solution to the Strong *CP* Problem (I)

The strong *CP* problem:

- Axial QCD anomaly $\rightarrow \mathscr{L}_{\mathrm{QCD}}^{\mathrm{eff}} \supset \bar{\theta}\,\frac{\alpha_s}{8\pi}\mathrm{Tr}\left[G_{\mu\nu}\widetilde{G}^{\mu\nu}\right]$ w/ $\bar{\theta} = \theta + \arg\{\det M_q\}$.
- Neutron electric dipole moment $d_n \simeq 5\times 10^{-16}\,\bar{\theta}\,\mathrm{e\ cm} \lesssim 3\times 10^{-26}\,\mathrm{e\ cm}$.
- QCD vacuum angle $\bar{\theta} \lesssim 10^{-10}$. Expectation $\bar{\theta} \sim \mathcal{O}(1)$. $\Rightarrow$ Why so tiny?

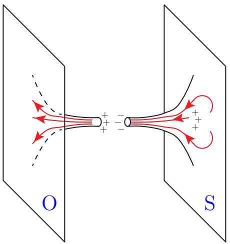
One solution: Promote $\bar{\theta}$ to dynamical real scalar field with VEV at 0.

[Peccei & Quinn '77; Weinberg '78; Wilczek '78]

- The axion: pseudo-NG boson of a spontaneously broken global $U(1)_{\mathrm{PQ}}$.
- QCD instanton-induced effective potential after the QCD phase transition:

$$V_a = \Lambda_{\mathrm{QCD}}^4\left[1-\cos\left(\bar{\theta}-a/f_a\right)\right]\,, \quad \langle a\rangle = \bar{\theta}\,f_a\,.$$

The Peccei-Quinn Solution to the Strong *CP* Problem (II)



[Fig. from J.E. Kim, 1308.0344 [hep-th]]

But: Any global symmetry is believed to be broken by quantum gravity effects!

[Kamionkowski & March-Russell ’92; Barr & Seckel ’92; Holman et al. ’92; Banks & Seiberg ’11]

- Why is $\bar{\theta}$ so small? $\rightarrow$ Why is the global PQ symmetry of such high quality?
- Answer: Approximate accidental $U(1)_{\rm PQ}$ due to exact gauge symmetry.

Our idea: Protect PQ symmetry by means of gauged discrete R symmetry, Z_N^R.

An Anomaly-Free Discrete R Symmetry for the MSSM (I)

Strong motivation for Z_N^R in SUSY phenomenology and model building:

[Giudice & Masiero '88; Yanagida '97; Dine & Kehayias '10] [Dimopoulos & Georgi '81; Sakai & Yanagida '82; Weinberg '82] [Izawa & Yanagida '97]

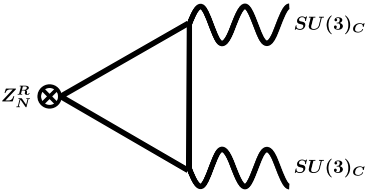
- No large μ term, no dangerous proton decay, no large $\langle W \rangle$ (i.e. negative Λ).
- Possibly remanant subgroup of continuous *stringy* $U(1)_R$ symmetry.
- If $U(1)_R$ gauged, remnant Z_N^R gauged and not broken by quantum gravity.

Rendering the Z_N^R symmetry anomaly-free:

[Ibanez '93]

- Generation-independent Z_N^R with $N = 3, 4, 5, ..$ that commutes with $SU(5)$.
- $Z_N^R\,[SU(3)_C]^2$ and $Z_N^R\,[SU(2)_L]^2$ anomaly coefficients: $\mathcal{A}_R^{(C)} \overset{(N)}{=} \mathcal{A}_R^{(L)} \overset{(N)}{=} -6$.
- Given solely the MSSM particle content, only Z_3^R and Z_6^R anomaly-free.

An Anomaly-Free Discrete *R* Symmetry for the MSSM (II)



$N \neq 3,6 \Rightarrow$ Extra matter sector required. *Natural* consequende of gauged Z_N^R.

- Introduce k pairs of vector-like quark & anti-quark fields, $Q_i \sim \mathbf{5}_i$ & $\bar{Q}_i \sim \mathbf{5}_i^*$.
- R charges such that $k\left(r_Q + r_{\bar{Q}} - 2\right) \overset{(N)}{=} +6$. In most cases, $r_Q + r_{\bar{Q}} \neq 0, 2$.
- $W_Q^{\mathrm{ren}} = 0. \Rightarrow$ global $SU(k)_Q^V \times SU(k)_Q^A \times U(1)_Q^V \times U(1)_Q^A$ flavour symmetry.

Rendering the Extra Quark Flavours Massive

Couple new matter sector to SM singlet P that acquires VEV above the EW scale:

$$W_Q \supset \frac{\lambda_i}{M_{\rm Pl}^{n-1}} P^n \left(Q\bar{Q}\right)_i \,, \quad m_{Q_i} = \frac{\lambda_i}{M_{\rm Pl}^{n-1}} \left<P\right>^n , \quad n = 1,2\,.$$

- $n\,k$ possible values for r_P, the R charge of P, for each combination of N, n, k.
- Add singlets $\bar{P}$ and X with $r_{\bar{P}} = -r_P$ and $r_X = 2$. Restrict to values of r_P s. t.

$$W_P^{\rm ren} = \kappa X \left[\frac{\Lambda^2}{2} - P\bar{P}\right] , \quad \left<X\right> \sim m_{3/2}\,, \quad \left<P\right> = \frac{\Lambda}{\sqrt{2}} e^{A/\Lambda} , \quad \left<\bar{P}\right> = \frac{\Lambda}{\sqrt{2}} e^{-A/\Lambda} \,.$$

- Global $U(1)_P$. Coupling b/t new matter and new singlet sector $\rightarrow U(1)_{\rm PQ}$,

$$U(1)_P \times U(1)_Q^V \times U(1)_Q^A \rightarrow U(1)_{\rm PQ} \times U(1)_Q^V , \quad q_P = 1\,, \quad q_{\bar{P}} = -1\,.$$

- Colour anomaly: $\mathcal{A}_{\rm PQ} = k\, q_{Q\bar{Q}} = k\,(-n)$. Remniscent of KSVZ axion model.
- q_Q and $q_{\bar{Q}}$ eventually fixed by coupling to MSSM (e.g. $\bar{Q}\mathbf{10}H_d$ or $\bar{P}\bar{Q}\mathbf{10}H_d$).

Generation of the MSSM μ Term

$W_\mu = \mu H_u H_d$ forbidden by Z_N^R. Generated during / after R symmetry breaking.

- $N = 4$: $K \supset g H_u H_d$. $\Rightarrow$ R breaking $\rightarrow$ $W \supset \frac{g}{M_{\mathrm{Pl}}^2} \langle W \rangle H_u H_d = g\, m_{3/2} H_u H_d$.
- $N \neq 4$: Couple standard model singlet S with $r_s = -2$ to $H_u H_d$.

$$W_S^{\mathrm{ren}} = g_H H_u H_d\, S + m_{3/2}^2 S + g_X m_{3/2} X\, S + g_{X^2} X^2\, S \quad \left(+m_S S^2\right)\ \left(+\lambda_S S^3\right).$$

- In the PQ-breaking vacuum: $\langle S \rangle = \mu / g_H \sim m_{3/2}$.

Same low-energy phenomenology as the PQ-NMSSM and the nMSSM:

[Jeong, Shoji & Yamaguchi '12] [Panagiotakopoulos & Tamvakis '99; Panagiotakopoulos & Pilaftsis '01]

- Singlino $\tilde{S}$ receives mass only from mixing with $\tilde{H}_{u,d}^0$. $\Rightarrow$ Lightest neutralino.
- Contributions to m_{h^0} of a few GeV from singlino loops, if $\tilde{H}_{u,d}^0$ are light.
- $\mathrm{BR}\left(h^0 \rightarrow \tilde{S}\tilde{S}\right) > 0.5$ at small $\tan\beta$. $\Rightarrow$ Soon tested at LHC-13 / LHC-14.

Our model: MSSM + extra **5**'s and **5***'s. + singlets P, $\bar{P}$, X + singlet S.

Outline

Bounds on the Number of Extra Matter Multiplets

- Require unification of the SM gauge couplings at the perturbative level,

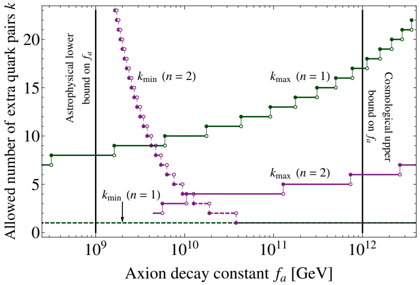
$$g_{\rm GUT}(m_{Q_i}, k) \leq \sqrt{4\pi} \;\Rightarrow\; k_{\max} = k_{\max}\left(f_a, n\right) ,$$

- and consistency with direct searches for heavy vector-like down-type quarks,

[ATLAS, $14.3\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8\,\mathrm{TeV}$, assuming a dominant coupling to the third generation of SM quarks via the operator $\bar{Q}\mathbf{10}H_d$]

$$m_{Q_i} \propto \left|\mathcal{A}_{\rm PQ}\right|^n \propto k^n , \quad m_{Q_i} \geq M_Q^{\min} = 590\,\mathrm{GeV} \;\Rightarrow\; k_{\min} = k_{\min}\left(f_a, n\right) .$$

Solve RGEs including the new matter:



$k_{\min}$ and $k_{\max}$ translate into lower bounds on the axion decay constant f_a:

$$g_{\rm GUT}\left(f_a^{\rm min,p}, n, k\right) = \sqrt{4\pi} ,$$
$$M_Q\left(f_a^{\rm min,m}, n, k\right) = M_Q^{\min} .$$

$$\max\left\{f_a^{\rm min,p}, f_a^{\rm min,m}\right\} \leq f_a .$$

$$f_a^{\rm min,i} = f_a^{\rm min,i}(k, n) , \quad \mathrm{i} = \mathrm{p}, \mathrm{m} .$$

Shifts in the QCD Vacuum Angle

Higher-dim. operators explicitly break the $U(1)_{\mathrm{PQ}}$, Most relevant operators in W:

$$W \supset \frac{P^p S^s}{p!\, s!\, M_{\mathrm{Pl}}^c}, \frac{\bar{P}^{\bar{p}} S^s}{\bar{p}!\, s!\, M_{\mathrm{Pl}}^c}, \frac{m_{3/2}^m P^p X^x}{p!\, x!\, M_{\mathrm{Pl}}^c}, \frac{m_{3/2}^m \bar{P}^{\bar{p}} X^x}{\bar{p}!\, x!\, M_{\mathrm{Pl}}^c}, \qquad r_P(p-\bar{p}) + 2(m+x-s) \overset{(N)}{=} 2\,.$$

Non-standard contributions to the axion potential (from F- and A-terms):

$$\Delta V_a = M^4 \cos\left(p\frac{a}{\sqrt{2}\Lambda}\right), \qquad M = M\left(N, n, k, f_a, m_{3/2}, \langle S\rangle, \langle X\rangle\right)$$

These distortions of V_a induce shifts in the axion VEV, $\langle a\rangle = \left(\bar{\theta} + \Delta\bar{\theta}\right) f_a$:

$$\Delta\bar{\theta} \sim \frac{p}{|\mathcal{A}_{\mathrm{PQ}}|}\frac{M^4}{\Lambda_{\mathrm{QCD}}^4} \leq 10^{-10} \;\Rightarrow\; M^4 \leq 10^{-10}\frac{|\mathcal{A}_{\mathrm{PQ}}|}{p}\Lambda_{\mathrm{QCD}}^4 \;\Rightarrow\; f_a \leq f_a^{\max}\,.$$

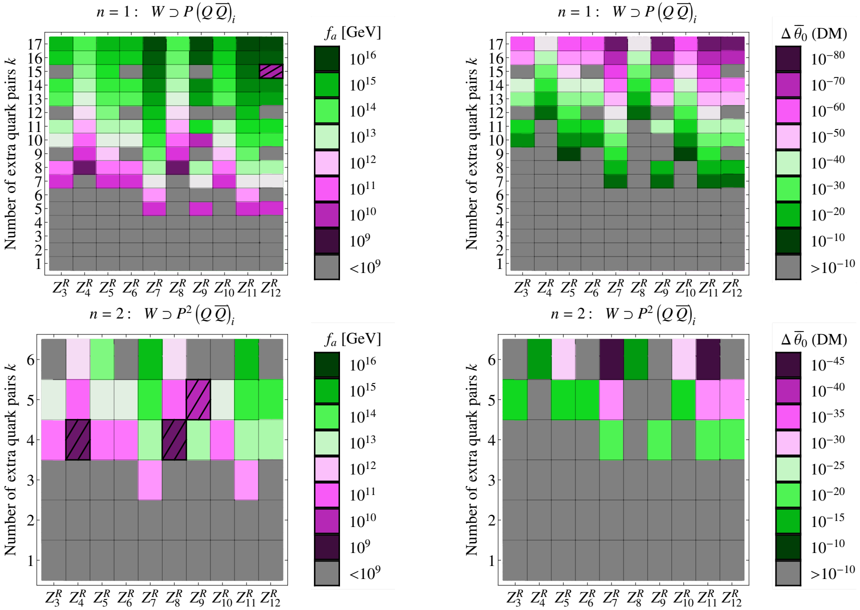
$$f_a \leq \min\left\{f_a^{\max,S}, f_a^{\min,X}\right\}.$$

$$10^9\,\mathrm{GeV} \lesssim f_a \lesssim 10^{12}\,\mathrm{GeV}\,.$$

(N, n, k, r_P) viable if window of viable f_a.

- We scan 1950 combinations of N, n, k and r_P for $m_{3/2} = \langle S\rangle = \langle X\rangle = 1\,\mathrm{TeV}$.

Phenomenologically Viable Scenarios



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Idea: Approximate accidental $U(1)_{\rm PQ}$ due to exact gauged discrete R symmetry.

- New matter sector in order to render the Z_N^R anomaly-free, Q_i & $\bar{Q}_i$.
- New singlet sector in order to provide masses to the new matter, P, $\bar{P}$ & X.
- Singlet S to generate the MSSM μ term.

Phenomenological constraints on N, n, k, r_P, f_a based on:

- Lower bound on the mass of heavy down-type quarks, $M_Q^{\rm min} = 590\,{\rm GeV}$.
- SM gauge coupling unification at the perturbative level, $g_{\rm GUT} \leq \sqrt{4\pi}$.
- Not too large a shift in the QCD vacuum angle, $\bar{\theta} < 10^{-10}$.
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Result: Large landscape of viable solutions. Lower bounds on $\bar{\theta}$ in case of axion DM.

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Thank you for your attention!