A Grand Color Massless Quark Solution to the Strong CP Problem

Ravneet Bedi

University of Minnesota

In collaboration with Tony Gherghetta and Keisuke Harigaya

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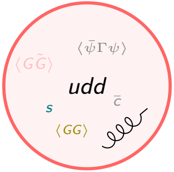
The "problem"

$$\mathcal{L}_{QCD} \supset \frac{\theta}{32\pi^2} G\widetilde{G}$$



QCD tells us that nEDM [Crewther et al '79]

$$d_n \simeq 3 \times 10^{-16}\theta \; e \cdot \mathrm{cm}$$

$$\theta \lesssim 10^{-10} \; !$$

Minimum of the potential at $\theta = 0$ [Peccei, Quinn '77]

$\Longrightarrow$ Making θ dynamical means it can relax to the minimum

$$\theta \to \frac{a}{f_a}$$

with 10^{-5} eV $\lesssim m_a \lesssim 10^{-2}$ eV

Axion mass

Ground state of QCD vacuum?

- $A_\mu = 0$ is one candidate,

  But $\exists$ gauge transformations of $A_\mu = 0$

  ['t Hooft '76; Callan '76]

- The "tunneling" amplitude between them

$$\sim \; e^{-S} = e^{-8\pi^2/g^2}$$

- The physical state " θ vacua" is a linear combination of all such states.

- Since $a \leftrightarrow a/f_a$, we have

$$m_a^2 f_a^2 \quad \sim \quad \left(\prod m_q\right) \; \Lambda_{QCD}^{4-\#\text{quarks}} \; \underbrace{e^{-\frac{8\pi^2}{g^2}}}_{\text{Exponentially suppressed}} \; \left(\frac{8\pi^2}{g^2}\right)^6$$

Overcoming the suppression by increasing g 🤔?

- Adding more matter, or QCD like dynamics in the UV

Strong coupled at another scale Λ_{SI}

And couples to the axion

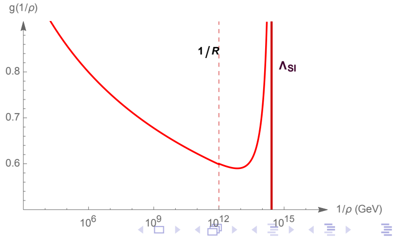
[Fukuda et al '15; Gherghetta et al '16; Agrawal et al '17;...]

$$\mathcal{L} \supset \frac{a}{f_a}\left(G\tilde{G} + G'\tilde{G}'\right)$$

- Other means of modifying the running of the coupling

5-d dynamics can enhance axion mass significantly

[Gherghetta et al '20]



Massless up Quark

Other solutions to the strong CP problem?

- CP violation due to the θ term $\sim$ Im $[e^{-i\theta}\det(Y_u Y_d)]$
- Is $\det(Y_u Y_d) = 0$ possible? In particular, is $m_u = 0$? [Georgi, McArthur '81]
- Within QCD,

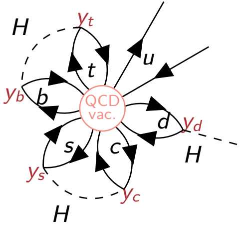
$$m_u \sim \frac{m_d m_s}{\Lambda_{QCD}}$$

accounts for $\sim 13\%$, only an order of magnitude away [Alexandrou et al '20]

Dynamics external to QCD?

Using "heavy axion" dynamics? [Hook '14; Agrawal, Howe '17; Gupta et al '20; Cordova '24]

Another Massless Quark Solution



$$y_u \sim \underbrace{\left(\prod \frac{y_q}{4\pi}\right)}_{\sim 10^{-18}} \left(\frac{8\pi^2}{g^2}\right)^6 e^{-\frac{8\pi^2}{g^2}}$$

How can we possibly generate the up Yukawa?

- Assume $y_q \sim 4\pi$ in the UV and run them down to the SM [Gupta et al '20]
- Each generation in a different gauge group [Agrawal, Howe '17]

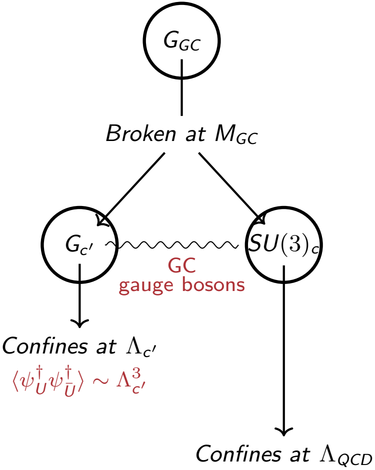
$$SU(3)^3 \to SU(3)_{QCD}$$
$$(y_u, y_s, y_b) \sim \#(y_d, y_c, y_t)$$

More accurately,

only $y_b \sim \# y_t$ [Csaki et al '19]

What else?

Generating a quark mass



Consider

$$SU(N+3) \to SU(N) \times SU(3)$$

$$\Psi_U(\square) \to \psi_U(\square, \mathbf{1}), \;\; U(\mathbf{1}, \square)$$

The $SU(N+3)/SU(3)$ gauge bosons result in operators

$$\mathcal{L} \supset \frac{\psi_U^\dagger \psi_{\bar{U}}^\dagger U \bar{U}}{M_{GC}^2} \sim \underbrace{\frac{\Lambda_{c'}^3}{M_{GC}^2}}_{m_U} U\bar{U}$$

[Dimopoulos, Susskind '79]

But directly applying this to the SM results in EWSB if

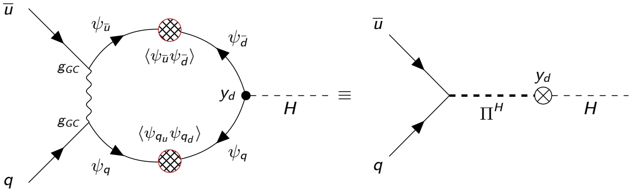
$$\langle \psi^\dagger_{q_u} \psi^\dagger_{\bar{u}} \rangle \neq 0$$

We need $\langle \psi_{q_u} \psi_{q_d} \rangle, \ \langle \psi_{\bar{d}} \psi_{\bar{u}} \rangle \neq 0$

$SU(2N+3) \to Sp(2N) \times SU(3)_c$ allows this

	$SU(2N+3)$	$Sp(2N)$	$SU(3)_c$	$SU(2)_L$
$\Psi_q \equiv \begin{pmatrix} q \\ \psi_q \end{pmatrix}$	$\square$	$\mathbf{1}$ $\square$	$\square$ $\mathbf{1}$	$\square$
$\Psi_{\bar{u}} \equiv \begin{pmatrix} \bar{u} \\ \psi_{\bar{u}} \end{pmatrix}$	$\bar{\square}$	$\mathbf{1}$ $\square$	$\bar{\square}$ $\mathbf{1}$	$\mathbf{1}$
$\Psi_{\bar{d}} \equiv \begin{pmatrix} \bar{d} \\ \psi_{\bar{d}} \end{pmatrix}$	$\bar{\square}$	$\mathbf{1}$ $\square$	$\bar{\square}$ $\mathbf{1}$	$\mathbf{1}$

[Valenti, Vecchi, Xua '22]



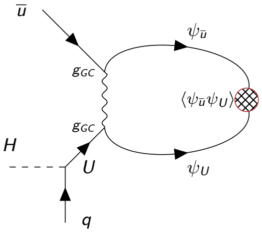
$$y_u \simeq \underbrace{\frac{N}{4} \frac{g_{GC}^2}{g_2^2} \frac{\Lambda_{\mathrm{Sp}}^2}{M_{\mathrm{GC}}^2}}_{\simeq 1/2} y_d$$

$\Lambda_{\mathrm{Sp}} \sim M_{\mathrm{GC}} \leftrightarrow$ large N

SM Yukawas with Grand Color

$$\mathcal{L} \supset -m_U \Psi_U \Psi_{\bar{U}} - \lambda_U \Psi_q \Psi_{\bar{U}} H$$

$$y_u = Min\left(\frac{N g_{\rm GC}^2}{16\pi^2} \frac{\Lambda_{\rm Sp}^3}{m_U M_{GC}^2} \frac{\lambda_U y_d \Lambda_{\rm Sp}}{\sqrt{(16\pi^2 m_U)^2 + (\lambda_U y_d \Lambda_{\rm Sp})^2}}, 1 \right) \lambda_U$$



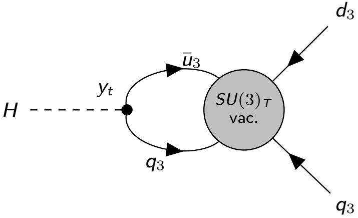
How does this generalize to two or three generations

- Without a VLQ, two generation model generates a very large strange Yukawa.
- Reproduces the SM Yukawas for the first and the second generation with a VLQ

$$\mathcal{L} \supset -\widetilde{Y}^u_{i2} \Psi_{q_i} \Psi_{\bar{u}_2} H - \widetilde{Y}^d_{ia} \Psi_{q_i} \Psi_{\bar{d}_a} \widetilde{H} - \lambda_{Ui} \Psi_{q_i} \Psi_{\bar{U}} H - m_U \Psi_U \Psi_{\bar{U}}$$

for $N \sim 5 - 12$, $\Lambda_{\rm Sp} \sim 10^6 - 10^{12}$GeV

The top Yukawa results in a severe Higgs-pion mixing resulting in EWSB.



We can instead consider the gauge group

$$SU(2N+3) \times SU(3)_T$$

$$SU(3) \times SU(3)_T \xrightarrow{v_T} SU(3)_c$$

assuming the b quark is massless in the UV

Can generate a bottom Yukawa $\sim 10^{-15} - 10^{-2}$

The $SU(3) \times SU(3)_T$ breaking Higgs field couples to all three generations resulting in the CKM mixing

We can also add VLQs to this sector

$$\mathcal{L} = -m_B B\bar{B} - y_t q_3 \bar{u}_3 H - \lambda_B q_3 \bar{B}\widetilde{H} + y_a^B B\bar{d}_a \Phi_3 + \text{h.c.}$$

Summary

- The axion can solve the Strong CP Problem even outside the mass range $10^{-5} - 10^{-2}$eV.
- The strong dynamics can generate the up (and bottom) Yukawa on its own
- Maybe axions are not required after all
- Other implications of strong dynamics in the UV...

Thank You